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RESEARCH MEMORANDUM

THEORETICAL PERFORMANCE OF MIXTURES OF LIQUID AMMONIA AND HYDRAZINE AS FUEL WITH LIQUID FLUORINE AS OXIDANT FOR ROCKET ENGINES

By Sanford Gordon and Vearl N. Huff

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NATIONAL ADVISORY COMMITTEE FOR AERONAUTICS

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SUMMARY

Theoretical values of rocket performance parameters for two mixtures of liquid ammonia and hydrazine as fuels with liquid fluorine as oxidant were calculated on the assumption of equilibrium composition during the expansion process for a wide range of fuel-oxidant and expansion ratios. The parameters included were specific impulse, combustion-chamber temperature, nozzle-exit temperature, equilibrium composition, mean molecular weight, characteristic velocity, coefficient of thrust, ratio of nozzle-exit area to throat area, specific heat at constant pressure, coefficient of viscosity, and coefficient of thermal conductivity. Exponents were calculated that permit determination of specific impulse over a range of chamber pressures.

The maximum value of specific impulse at sea level for a chamber pressure of 300 pounds per square inch absolute (20.41 atm) was 313.6 pound-seconds per pound for the fuel mixture containing 36.3 percent ammonia by weight and 311.9 pound-seconds per pound for the fuel mixture containing 87 percent ammonia by weight.

INTRODUCTION

Both ammonia and hydrazine have been of interest for a number of years as possible rocket fuels because of their high theoretical specific impulse with several oxidants. Extensive data exist in the literature on their availability and cost, and on their physical, chemical and handling properties.

Interest has also been shown in mixtures of ammonia and hydrazine, inasmuch as some of the properties of the mixtures are more desirable than those of the separate fuels (ref. 1). Ammonia, for example, depresses the relatively high freezing point of hydrazine, whereas hydrazine lowers slightly the vapor pressure of the ammonia.

Fluorine is of interest as a rocket oxidant because of its high performance with many fuels. Data on its properties are also available in the literature.

Calculations were made at the NACA Lewis laboratory to determine the theoretical performance of two mixtures of liquid ammonia and hydrazine as fuels with liquid fluorine as oxidant as part of a series of calculations on propellants containing the chemical elements hydrogen, fluorine, and nitrogen (refs. 2 to 4) and in support of an experimental program. One of the fuel mixtures, containing 36.3 percent ammonia by weight, was suggested by the Bureau of Aeronautics, Department of the Navy, and is based on the data from reference 1. This mixture was selected as a compromise between a fuel having a desirable freezing point and one having high performance. The other fuel mixture, containing 87 percent ammonia by weight, was chosen to correspond to the lowest freezing point of any mixture of ammonia and hydrazine.

Data were calculated on the basis of equilibrium composition during expansion for a wide range of fuel-oxidant and expansion ratios. The performance parameters included are specific impulse, combustion-chamber temperature, nozzle-exit temperature, equilibrium composition, mean molecular weight, characteristic velocity, coefficient of thrust, ratio of nozzle-exit area to throat area, specific heat at constant pressure, coefficient of viscosity, and coefficient of thermal conductivity. Exponents were calculated that permit determination of specific impulse over a range of chamber pressures for hydrogen with fluorine and ammonia with fluorine as well as mixtures of ammonia and hydrazine with fluorine.

So that data based on the assumptions of equilibrium and frozen composition during the expansion process could be compared, several additional calculations were made with the assumption of frozen composition.

SYMBOLS

The following symbols are used in this report:

A number of equivalent formulas (function of pressure and molecular weight; see ref. 5)

a local velocity of sound, ft/sec

C_F coefficient of thrust, Ig/c^*

C_p^o molar specific heat at constant pressure, cal/(mole)(°K)

c_p specific heat at constant pressure, cal/(g)(°K)

c_v specific heat at constant volume, cal/(g)(°K)

c^* characteristic velocity, ft/sec, gP_cS_t/w

[redacted]

D_A $\left(\frac{\partial \log A}{\partial \log T}\right)_s$

D_i $\left(\frac{\partial \log p_i}{\partial \log T}\right)_s$

g acceleration due to gravity, 32.174 ft/sec^2

H_T^o sum of sensible enthalpy and chemical energy, cal/mole

h sum of sensible enthalpy and chemical energy per unit weight, $\frac{\sum_i n_i(H_T^o)_i}{nM}$, cal/g

I specific impulse, lb-sec/lb

k coefficient of thermal conductivity, cal/(sec)(cm)(^{o}K)

M molecular weight

n number of moles; exponent

P pressure

p partial pressure

R universal gas constant (consistent units)

r equivalence ratio, ratio of number of fluorine atoms to hydrogen atoms

S nozzle area, sq ft

T temperature, ^{o}K

w rate of flow, lb/sec

γ_A $\left(\frac{\partial \log A}{\partial \log T}\right)_P$

γ_i $\left(\frac{\partial \log n_i}{\partial \log T}\right)_P$

γ_s $\left(\frac{\partial \log P}{\partial \log \rho}\right)_s$

[redacted]

μ	coefficient of viscosity, g/(cm)(sec) = poise
ρ	density, g/cc

Subscripts:

c	combustion chamber
e	nozzle exit
frozen	composition assumed frozen 2901
i	product of combustion
max	maximum
P	constant pressure
s	constant entropy
t	nozzle throat
x	any point in nozzle

CALCULATION OF PERFORMANCE DATA

Calculations of the performance data were made with a Bell computer and an IBM Card-Programmed Electronic Calculator as described in reference 2. The assumptions, thermodynamic data, and transport properties used for the calculations are the same as those of reference 2.

The products of combustion were assumed to be ideal gases and included the following substances: hydrogen fluoride HF, hydrogen H_2, nitrogen N_2, fluorine F_2, atomic fluorine F, atomic hydrogen H, and atomic nitrogen N. The dissociation energy of F_2 was taken to be 35.6 kilocalories per mole (ref. 6). Physical and thermochemical properties of the propellants were taken from references 5 to 8 and are given in table I.

Composition of fuel mixtures. - Performance calculations were made for two fuel mixtures with liquid fluorine as the oxidant. One fuel was 36.3 percent ammonia and 63.7 percent hydrazine by weight, and the other was 87 percent ammonia and 13 percent hydrazine by weight. The heat of solution was neglected in estimating the heat of formation of each mixture.

[redacted]

Procedure for combustion conditions. - The following parameters were computed for five equivalence ratios for a chamber pressure of 300 pounds per square inch absolute: combustion temperature, equilibrium composition, enthalpy, mean molecular weight, derivative of the logarithm of pressure with respect to the logarithm of density at constant entropy γ_s, specific heat at constant pressure, coefficient of viscosity, coefficient of thermal conductivity, and entropy of the combustion products.

Procedure for exit conditions. - Equilibrium composition, mean
2901 molecular weight, pressure, derivative of the logarithm of pressure with respect to the logarithm of density at constant entropy γ_s, enthalpy of the products of combustion, specific heat at constant pressure, coefficient of viscosity, and coefficient of thermal conductivity were computed for each equivalence ratio by assuming isentropic expansion for three assigned exit temperatures selected to cover the exit pressure range from the nozzle-throat pressure to about 0.45 atmosphere.

Interpolation. - Parameters for pressures at and near the nozzle throat and for pressures corresponding to altitudes of 0, 10,000, 20,000, and 30,000 feet were interpolated by means of cubic equations between each pair of the assigned exit temperatures. The functions and their first derivatives used in the interpolations are described in reference 2.

The errors due to interpolation were checked for several cases. The values presented for all performance parameters appear to be correctly interpolated or in error at most by two or three units in the last place tabulated.

Formulas. - The formulas used in computing the various parameters are given in reference 2 and are summarized as follows:

Specific impulse, lb-sec/lb:

$$I = 294.98\sqrt{\frac{h_c - h_e}{1000}} \tag{1}$$

Throat area per unit flow rate, (sq ft)(sec)/lb, (pressure in atm):

$$S_t/w = \frac{1.3144T_t}{P_tM_ta} \tag{2}$$

Characteristic velocity, ft/sec:

$$c^* = gP_cS_t/w = 32.174P_cS_t/w \tag{3}$$

Coefficient of thrust:

$$C_F = Ig/c^* = 32.174I/c^* \tag{4}$$

Nozzle-exit area per unit flow rate, (sq ft)(sec)/lb, (pressure in atm):

$$S_e/w = \frac{0.040853T_e}{P_e M_e I} \tag{5}$$

Ratio of nozzle-exit area to throat area: 2901

$$S_e/S_t = \frac{S_e/w}{S_t/w} \tag{6}$$

Specific heat at constant pressure, cal/(g)($^\circ$K):

$$c_p = \frac{1}{nMT}\left[T\sum_i n_i(C_p^o)_i + \sum_i n_i(H_T^o)_i\ Y_i - \sum_i n_i(H_T^o)_i\ Y_A\right] \tag{7}$$

Derivative of the logarithm of pressure with respect to the logarithm of density at constant entropy:

$$\gamma_s = \frac{\sum_i p_i D_i}{P(D_A-1)} \tag{8}$$

Coefficient of viscosity, poise:

$$\mu = \frac{PM}{\sum_i \frac{p_i}{(\mu_i/M_i)}} \tag{9}$$

Coefficient of thermal conductivity, cal/(sec)(cm)($^\circ$K):

$$k = \mu\left(c_p + \frac{5}{4}\frac{R}{M}\right) \tag{10}$$

When composition is assumed to be frozen, the partial derivatives Y_i and Y_A in equation (7) are equal to zero, and the partial derivatives D_i and D_A in equation (8) are equal to $\frac{c_{p,frozen}}{R/M}$. Therefore, equations (7) and (8) become

$$c_{p,frozen} = \frac{\sum_i n_i (C_p^o)_i}{nM} \tag{11}$$

and

$$\gamma_{s,frozen} = \frac{c_{p,frozen}}{c_{p,frozen} - R/M} = \left(\frac{c_p}{c_v}\right)_{frozen} \tag{12}$$

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The values of viscosity and thermal conductivity for mixtures of combustion gases calculated by means of equations (9) and (10) are only approximate. When more reliable transport properties for the various products of combustion become available, a more rigorous procedure for computing the properties of mixtures may also be justified.

THEORETICAL PERFORMANCE DATA

For a combustion pressure of 300 pounds per square inch absolute, the calculated values of the performance parameters specific impulse, temperature, mean molecular weight, characteristic velocity, coefficient of thrust, and ratio of nozzle-exit area to throat area are given in table II at exit pressures corresponding to altitudes of 0, 10,000, 20,000, and 30,000 feet. The values of pressure corresponding to the assigned altitudes were taken from reference 9. As an aid to engine design, the values of the parameters within the rocket nozzle for 80, 90, 100, 110, and 120 percent of the throat pressure are presented in table III. Equilibrium composition, γ_s, specific heat at constant pressure, coefficient of viscosity, coefficient of thermal conductivity, and mean molecular weight in the combustion chamber at assigned exit temperatures are given in table IV. The mole fraction of F_2 was always less than 0.00002 and therefore was not tabulated.

Parameters. - Curves of specific impulse for four altitudes are shown in figure 1 plotted against weight percent fuel. The maximum value of specific impulse for the sea-level curve is 313.6 pound-seconds per pound at 28.4 percent fuel by weight for the fuel mixture containing 36.3 percent ammonia by weight and 311.9 pound-seconds per pound at 24.9 percent fuel by weight for the fuel mixture containing 87 percent ammonia.

The maximum values of specific impulse and the weight percentages at which they occur were obtained by numerical differentiation of the calculated values and are shown in figure 2 as functions of altitude. The maximum specific impulse increases 14 percent for a change in altitude from sea level to 30,000 feet for both fuel mixtures.

Curves of combustion-chamber temperature and nozzle-exit temperature for various altitudes are presented in figure 3 as functions of weight percent fuel. The maximum combustion temperatures calculated are 4354° and 4306° K for the 36.3 and 87 percent ammonia fuel mixtures, respectively (table II). The maximums of the exit-temperature curves occur near the stoichiometric ratio.

Characteristic velocity and coefficient of thrust are plotted in figure 4, and the ratio of the area at the nozzle exit to the area at the throat is plotted in figure 5, against weight percent fuel. 2901

Curves of mean molecular weight in the combustion chamber and nozzle exit are plotted against weight percent fuel in figure 6.

Curves of specific heat at constant pressure, coefficient of viscosity, and coefficient of thermal conductivity for six pressures are plotted in figures 7, 8, and 9, respectively, as functions of weight percent fuel.

Chamber-pressure effect. - According to data of reference 4, the values of the parameters I, c^*, and S_e/S_t for hydrazine and fluorine are very nearly linear with the logarithm of chamber pressure for a fixed equivalence ratio and expansion ratio. This linearity permitted the data to be correlated according to the following equations:

$$I = I_{300}\left(\frac{P_c}{300}\right)^n \tag{13}$$

$$c^* = c^*_{300}\left(\frac{P_c}{300}\right)^n \tag{14}$$

$$S_e/S_t = (S_e/S_t)_{300}\left(\frac{P_c}{300}\right)^n \tag{15}$$

where I_{300}, c^*_{300}, and $(S_e/S_t)_{300}$ are the values of these parameters at 300 pounds per square inch absolute; I, c^*, and S_e/S_t are the values of these parameters at any chamber pressure P_c; P_c is in pounds per square inch absolute; and the exponent n is a function of fuel-oxidant and expansion ratios for each parameter. The following equation for obtaining the value of n for specific impulse was derived in reference 4:

$$n = 86.4554\,\frac{T_e}{I^2}\left(\frac{1}{M_c} - \frac{1}{M_e}\right) \tag{16}$$

In the case of hydrazine and fluorine, it was found that equation (13) could be used with the exponent of equation (16) over a chamber-pressure range of 4 to 1 with a maximum error of a few tenths of an impulse unit over a wide range of equivalence ratios. This chamber-pressure correlation was also checked for one equivalence ratio for several other propellants and found to apply over a similar pressure range to about the same accuracy. The values of n were therefore computed by means of equation (16) for the other propellants in this series of reports; namely, hydrogen with fluorine, ammonia with fluorine, and mixtures of ammonia and hydrazine with fluorine. These values of n were used together with the specific-impulse data for 300 pounds per square inch absolute to construct figure 10, which, with the aid of equation (13), permits determination of specific impulse for a range of chamber pressures.

To illustrate the use of these curves, suppose it is desired to obtain the value of specific impulse for a chamber pressure of 1000 pounds per square inch and an expansion ratio of 136.1 for hydrogen and fluorine at the stoichiometric mixture ratio. From figure 10(d), the value of I_{300} is read as 413 (or more precisely, 412.8 by interpolating table III of ref. 2), and the value of n is read as 0.0114. From equation (13),

$$I = 412.8 \left(\frac{1000}{300}\right)^{0.0114}$$

$$= 412.8\ (1.0138)$$

$$= 418.5$$

which compares with the value of 418.47 obtained by direct computation.

Equations similar to equation (16) may be derived for the exponents n for c^* and S_e/S_t; however, these equations could not be evaluated numerically, inasmuch as they involve partial derivatives that have not been calculated. The value of the exponents for c^* and S_e/S_t may, however, be computed from the values of these parameters at two chamber pressures, as was done in reference 4. The exponents computed for hydrazine and fluorine at the stoichiometric equivalence ratio (ref. 4) are about the same as those for hydrogen and fluorine at the same equivalence ratio computed from data of reference 2. Inasmuch as the values of these exponents are not critical, it is probably possible to apply the values of n for hydrazine and fluorine to the other propellants in this series of reports with small error. Greater accuracy can be obtained by additional performance computations at another chamber pressure.

Corrections for nonadiabatic or nonisentropic processes. - Equations are given in reference 4 that permit the calculation of specific impulse for nonisentropic expansion or for change in heat content of the propellant gases from the originally calculated data.

Frozen composition. - In order to compare data based on the assumptions of equilibrium and frozen composition during the expansion process, several additional calculations were made with frozen composition assumed. These values are presented in table V together with corresponding equilibrium data for the stoichiometric equivalence ratio and for two expansion ratios. The percentage differences in these parameters for frozen and equilibrium composition are considerably higher for expansion to an altitude of 30,000 feet than for expansion to sea level.

For a combustion pressure of 300 pounds per square inch absolute and an exit pressure of 1 atmosphere, the values of maximum specific impulse and the percentages of fuel by weight at which they occur are given in the following table for frozen and equilibrium composition:

Weight percent ammonia in fuel	Composition during expansion			
	Equilibrium		Frozen	
	I_{max}	Weight percent fuel	I_{max}	Weight percent fuel
36.3	313.6	28.4	292.2	31.8
87	311.9	24.9	290.8	27.5

Effect of percentage of ammonia in fuel. - A comparison of the data in this report with that of references 3 and 4 shows a nearly linear variation in I, c^*, and S_e/S_t with the percentage of ammonia in an ammonia-hydrazine fuel mixture at constant equivalence and expansion ratios. An example of this variation is given in figure 11, which is a plot of I, c^*, and S_e/S_t for the stoichiometric equivalence ratio as a function of weight percentage of ammonia in the fuel.

Similar curves may be plotted for any equivalence ratio and expansion ratio covered by the data in this report and in references 3 and 4 and may be used to obtain the performance of any mixture of ammonia and hydrazine with fluorine. However, because these curves are very nearly linear, only small errors in performance result from linear interpolation of the tabulated data.

Figure 7 of reference 10 shows the same nearly linear variation in I, c^*, and S_e/S_t with the percentage of ammonia in the fuel when oxygen bifluoride is the oxidant. The stoichiometric curves of this figure are also given in figure 11 of this report for comparison.

Inasmuch as the difference in performance between ammonia and hydrazine is only about 4 specific impulse units with fluorine as oxidant, but is about 13 units with oxygen, hydrazine is more likely to be used with oxygen than with fluorine. However, ammonia is considerably cheaper and more available than hydrazine, and, except in special applications, ammonia appears to be the more practical rocket fuel. Mixtures of ammonia and hydrazine when used are likely to be selected for better physical properties and greater availability than hydrazine and slightly better performance and possibly higher combustion efficiency than ammonia.

Lewis Flight Propulsion Laboratory
National Advisory Committee for Aeronautics
Cleveland, Ohio, April 17, 1953

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TABLE I. - PROPERTIES OF LIQUID PROPELLANTS

Properties	Ammonia	Hydrazine	Fluorine
Molecular weight, M	17.032	32.048	38.00
Density, g/cc	[a]0.68 (at -33.4° C)	[a]1.011 (at 15° C)	[b]1.54 (at -196° C)
Freezing point, °C	[c]-77.76	[c]1.5	[c]-217.96
Boiling point, °C	[c]-33.43	[c]113.5	[c]-187.92
Enthalpy of formation (from elements at 25° C), ΔH_f, kcal/mole	[d]-17.14 (at -33.43° C)	[d]12.05 (at 25° C)	[d]-3.030 (at -187.92° C)
Enthalpy of vaporization, ΔH, kcal/mole	[c]5.581 (at -33.43° C)	[c]10 (at 113.5° C)	[c]1.51 (at -187.92° C)
Enthalpy of fusion, ΔH, kcal/mole	[c]1.351 (at -77.76° C)	------	[c]0.372 (at -217.96° C)

[a] Reference 7.
[b] Reference 8.
[c] Reference 6.
[d] Reference 5.

[redacted]

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TABLE II. - CALCULATED PERFORMANCE OF MIXTURE OF LIQUID AMMONIA AND HYDRAZINE WITH LIQUID FLUORINE

(a) Fuel, 36.3 percent ammonia and 63.7 percent hydrazine by weight.

[Combustion-chamber pressure, 300 lb/sq in. abs]

Propellant			Combustion chamber		Characteristic velocity, c^*, ft/sec	Nozzle exit[b]						
Equivalence ratio, r	Weight percent fuel	Density,[a] g/cc	Temperature, T_c, ^oK	Mean molecular weight, M_c		Altitude, ft	Pressure, P_e, atm	Temperature, T_e, ^oK	Mean molecular weight, M_e	Ratio of nozzle-exit area to throat area, S_e/S_t	Coefficient of thrust, C_F	Specific impulse, I, lb-sec/lb
1.2	23.42	1.299	4351	19.81	6919	0	1.0	2799	21.07	3.589	1.413	303.8
						10,000	.6876	2557	21.07	4.567	1.474	317.1
						20,000	.4594	2313	21.07	5.950	1.532	329.5
						30,000	.2968	2071	21.07	7.966	1.587	341.2
1.0	26.84	1.270	4354	19.15	7057	0	1.0	3188	20.86	3.930	1.427	312.9
						10,000	.6876	3044	21.01	5.169	1.495	328.0
						20,000	.4594	2883	21.15	6.967	1.562	342.6
						30,000	.2968	2697	21.27	9.632	1.627	356.8
0.8	31.44	1.233	4209	18.24	7086	0	1.0	2872	19.62	3.758	1.418	312.2
						10,000	.6876	2701	19.72	4.888	1.483	326.6
						20,000	.4594	2514	19.81	6.504	1.545	340.4
						30,000	.2968	2307	19.87	8.867	1.606	353.6
0.6	37.95	1.184	3860	17.09	6961	0	1.0	2433	18.06	3.602	1.410	305.0
						10,000	.6876	2253	18.10	4.637	1.472	318.5
						20,000	.4594	2062	18.12	6.099	1.531	331.2
						30,000	.2968	1862	18.13	8.220	1.587	343.3
0.4	47.84	1.117	3292	15.61	6665	0	1.0	1803	15.96	3.333	1.394	288.7
						10,000	.6876	1645	15.96	4.247	1.451	300.6
						20,000	.4594	1487	15.96	5.539	1.505	311.8
						30,000	.2968	1329	15.96	7.417	1.556	322.3

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[a]Based on following densities: F_2, 1.54 at -196° C; NH_3, 0.68 at -33.4° C; N_2H_4, 1.011 at 15° C.
[b]Nozzle designed for exit pressure equal to ambient pressure corresponding to altitude indicated.

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TABLE II. - CALCULATED PERFORMANCE OF MIXTURE OF LIQUID AMMONIA AND HYDRAZINE WITH LIQUID FLUORINE - Concluded

(b) Fuel, 87 percent ammonia and 13 percent hydrazine by weight.

[Combustion-chamber pressure, 300 lb/sq in. abs]

Propellant			Combustion chamber		Characteristic velocity, c^*, ft/sec	Nozzle exit[b]						
Equivalence ratio, r	Weight percent fuel	Density,[a] g/cc	Temperature, T_c, °K	Mean molecular weight, M_c		Altitude, ft	Pressure, P_e, atm	Temperature, T_e, °K	Mean molecular weight, M_e	Ratio of nozzle-exit area to throat area, S_e/S_t	Coefficient of thrust, C_F	Specific impulse, I, lb-sec/lb
1.2	20.56	1.242	4301	19.79	6877	0	1.0	2668	20.88	3.506	1.408	300.9
						10,000	.6876	2432	20.88	4.458	1.468	313.8
						20,000	.4594	2190	20.88	5.806	1.525	325.9
						30,000	.2968	1966	20.88	7.768	1.578	337.2
1.0	23.70	1.206	4306	19.11	7026	0	1.0	3127	20.74	3.912	1.426	311.3
						10,000	.6876	2977	20.88	5.136	1.494	326.2
						20,000	.4594	2809	21.01	6.903	1.560	340.7
						30,000	.2968	2613	21.10	9.505	1.624	354.7
0.8	27.97	1.161	4138	18.15	7036	0	1.0	2768	19.42	3.717	1.415	309.6
						10,000	.6876	2592	19.50	4.820	1.480	323.6
						20,000	.4594	2399	19.57	6.389	1.542	337.1
						30,000	.2968	2189	19.61	8.674	1.600	350.0
0.6	34.11	1.101	3735	16.92	6868	0	1.0	2269	17.72	3.528	1.406	300.1
						10,000	.6876	2089	17.74	4.522	1.467	313.1
						20,000	.4594	1901	17.75	5.926	1.524	325.4
						30,000	.2968	1710	17.75	7.966	1.578	337.0
0.4	43.71	1.019	3049	15.25	6445	0	1.0	1579	15.44	3.241	1.388	278.0
						10,000	.6876	1436	15.44	4.122	1.444	289.2
						20,000	.4594	1294	15.44	5.366	1.496	299.6
						30,000	.2968	1154	15.44	7.170	1.545	309.4

[a]Based on following densities: F_2, 1.54 at -196° C; NH_3, 0.68 at -33.4° C; N_2H_4, 1.011 at 15° C.
[b]Nozzle designed for exit pressure equal to ambient pressure corresponding to altitude indicated.

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TABLE III. - CALCULATED PARAMETERS AT PRESSURES NEAR NOZZLE THROAT FOR MIXTURE OF LIQUID AMMONIA AND HYDRAZINE WITH LIQUID FLUORINE

(a) Fuel, 36.3 percent ammonia and 63.7 percent hydrazine by weight.

[Combustion-chamber pressure, 300 lb/sq in. abs; throat conditions correspond to $P_x/P_t = 1.0$; I = velocity of flow/g]

Equivalence ratio, r	Weight-percent fuel	$\frac{P_x}{P_t}$	Pressure, P_x, atm	Temperature, T_x, ^{o}K	Mean molecular weight, M_x	Ratio of nozzle area to throat area, S_x/S_t	Coefficient of thrust, C_F	Specific impulse, I, lb-sec/lb
1.2	23.42	1.2	14.01	4182	20.06	1.0351	0.5486	118.0
		1.1	12.85	4142	20.11	1.0083	.6069	130.5
		1.0	11.68	4100	20.17	1.0000	.6643	142.9
		.9	10.51	4053	20.23	1.0080	.7216	155.2
		.8	9.342	4001	20.30	1.0323	.7799	167.7
1.0	26.84	1.2	14.07	4196	19.39	1.0357	0.5447	119.5
		1.1	12.89	4159	19.45	1.0084	.6033	132.3
		1.0	11.72	4120	19.51	1.0000	.6609	145.0
		.9	10.55	4077	19.57	1.0081	.7185	157.6
		.8	9.378	4030	19.64	1.0327	.7770	170.4
0.8	31.44	1.2	14.00	4038	18.45	1.0348	0.5497	121.1
		1.1	12.83	3999	18.50	1.0082	.6080	133.9
		1.0	11.67	3957	18.55	1.0000	.6653	146.5
		.9	10.50	3910	18.60	1.0079	.7226	159.1
		.8	9.333	3858	18.67	1.0320	.7808	172.0
0.6	37.95	1.2	13.88	3671	17.26	1.0336	0.5589	120.9
		1.1	12.72	3628	17.30	1.0080	.6166	133.4
		1.0	11.57	3582	17.34	1.0000	.6735	145.7
		.9	10.41	3532	17.38	1.0077	.7303	158.0
		.8	9.254	3476	17.43	1.0311	.7879	170.5
0.4	47.84	1.2	13.71	3089	15.71	1.0315	0.5718	118.4
		1.1	12.57	3045	15.73	1.0075	.6287	130.2
		1.0	11.42	2997	15.75	1.0000	.6848	141.9
		.9	10.28	2943	15.78	1.0072	.7409	153.5
		.8	9.139	2883	15.80	1.0294	.7978	165.3

TABLE III. - CALCULATED PARAMETERS AT PRESSURES NEAR NOZZLE THROAT FOR MIXTURE OF LIQUID AMMONIA AND HYDRAZINE WITH LIQUID FLUORINE - Concluded

(b) Fuel, 87 percent ammonia and 13 percent hydrazine by weight.

[Combustion-chamber pressure, 300 lb/sq in. abs; throat conditions correspond to $P_x/P_t = 1.0$; I = velocity of flow/g]

Equivalence ratio, r	Weight-percent fuel	$\frac{P_x}{P_t}$	Pressure, P_x, atm	Temperature, T_x, °K	Mean molecular weight, M_x	Ratio of nozzle area to throat area, S_x/S_t	Coefficient of thrust, C_F	Specific impulse, I, lb-sec/lb
1.2	20.56	1.2	13.98	4126	20.02	1.0343	0.5506	117.7
		1.1	12.82	4087	20.08	1.0080	.6088	130.1
		1.0	11.65	4044	20.13	1.0000	.6660	142.4
		.9	10.49	3996	20.19	1.0080	.7233	154.6
		.8	9.321	3942	20.26	1.0321	.7814	167.0
1.0	23.70	1.2	14.06	4149	19.34	1.0358	0.5449	119.0
		1.1	12.89	4112	19.40	1.0085	.6034	131.8
		1.0	11.72	4073	19.45	1.0000	.6610	144.4
		.9	10.55	4030	19.52	1.0080	.7186	156.9
		.8	9.376	3982	19.59	1.0325	.7771	169.7
0.8	27.97	1.2	13.98	3964	18.35	1.0345	0.5512	120.5
		1.1	12.82	3924	18.39	1.0082	.6094	133.3
		1.0	11.65	3881	18.44	1.0000	.6666	145.8
		.9	10.49	3834	18.49	1.0079	.7239	158.3
		.8	9.320	3781	18.55	1.0318	.7820	171.0
0.6	34.11	1.2	13.85	3541	17.07	1.0332	0.5615	119.9
		1.1	12.69	3499	17.11	1.0079	.6190	132.2
		1.0	11.54	3452	17.14	1.0000	.6757	144.3
		.9	10.39	3401	17.18	1.0076	.7324	156.3
		.8	9.231	3344	17.23	1.0308	.7899	168.6
0.4	43.71	1.2	13.58	2834	15.32	1.0304	0.5814	116.5
		1.1	12.45	2788	15.34	1.0073	.6378	127.7
		1.0	11.32	2738	15.35	1.0000	.6933	138.9
		.9	10.18	2682	15.36	1.0070	.7489	150.0
		.8	9.053	2620	15.37	1.0284	.8052	161.3

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TABLE IV. - PROPERTIES AND COMPOSITION IN COMBUSTION CHAMBER AND FOLLOWING AN ISENTROPIC EXPANSION TO ASSIGNED EXIT TEMPERATURES

(a) Fuel, 36.3 percent ammonia, 63.7 percent hydrazine by weight; oxidant, fluorine.

[Combustion-chamber pressure, 300 lb/sq in. abs]

Temperature, T, °K	Pressure, P, atm	γ_s, $\left(\frac{\partial \log P}{\partial \log \rho}\right)_s$	Specific heat at constant pressure, c_p, cal/(g)(°K)	Coefficient of viscosity, μ, micropoise	Coefficient of thermal conductivity, k, microcal/(sec)(cm)(°K)	Mean molecular weight, M	Equilibrium composition, mole fraction					
							HF	H_2	N_2	F	H	N
r = 1.2 (23.42 percent fuel by weight)												
4351	20.41	1.1608	1.6261	1788	3131	19.814	0.60531	0.00608	0.13610	0.19331	0.04806	0.01112
4100	11.69	1.1612	1.4339	1712	2665	20.168	.63449	.00402	.14022	.17841	.03489	.00796
3000	1.355	1.2878	.4390	1334	743	21.051	.70630	.00003	.15028	.14220	.00073	.00046
2400	.5328	1.3311	.3794	1105	550	21.072	.70778	.00000	.15065	.14155	.00001	.00002
r = 1.0 (26.84 percent fuel by weight)												
4354	20.41	1.1541	1.9126	1752	3579	19.154	0.62034	0.01758	0.15109	0.11718	0.08202	0.01178
4100	11.16	1.1507	1.7892	1678	3217	19.537	.65413	.01481	.15583	.09813	.06852	.00858
3000	.6152	1.1748	.8590	1318	1288	21.053	.79020	.00392	.17218	.02041	.01256	.00073
2900	.4793	1.1847	.7707	1282	1139	21.139	.79818	.00320	.17300	.01576	.00936	.00050
r = 0.8 (31.44 percent fuel by weight)												
4209	20.41	1.1628	1.6417	1643	2921	18.242	0.60999	0.05056	0.17073	0.04823	0.11168	0.00881
3900	10.26	1.1649	1.4264	1551	2420	18.617	.64072	.05215	.17601	.03102	.09466	.00545
2900	1.063	1.2074	.7491	1222	1070	19.599	.70523	.07423	.18798	.00194	.03027	.00035
2500	.4460	1.2448	.5662	1079	746	19.811	.71458	.08405	.19018	.00027	.01088	.00005
r = 0.6 (37.95 percent fuel by weight)												
3860	20.41	1.1846	1.2740	1434	2035	17.086	0.54780	0.14004	0.19615	0.01022	0.10215	0.00362
3600	12.00	1.1882	1.1496	1357	1755	17.322	.55989	.15045	.19966	.00584	.08209	.00207
2500	1.151	1.2484	.6101	1013	757	18.044	.58923	.19138	.20905	.00009	.01022	.00003
2100	.4981	1.2932	.4951	879	556	18.120	.59180	.19630	.20995	.00001	.00195	.00000
r = 0.4 (47.84 percent fuel by weight)												
3292	20.41	1.2106	.9701	1145	1293	15.607	0.42763	0.30009	0.22771	0.00079	0.04324	0.00054
3000	11.50	1.2236	.8380	1066	1061	15.752	.43212	.31150	.23000	.00029	.02590	.00019
2000	1.546	1.3069	.5353	779	538	15.956	.43802	.32814	.23309	.00000	.00075	.00000
1500	.4761	1.3381	.4928	622	403	15.962	.43818	.32863	.23317	.00000	.00001	.00000

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CS-3 back

TABLE IV. - PROPERTIES AND COMPOSITION IN COMBUSTION CHAMBER AND FOLLOWING AN ISENTROPIC EXPANSION TO ASSIGNED EXIT TEMPERATURES - Concluded

(b) Fuel, 87 percent ammonia, 13 percent hydrazine by weight; oxidant, fluorine.

[Combustion-chamber pressure, 300 lb/sq in. abs]

Temperature, T, °K	Pressure, P, atm	γ_s, $\left(\frac{\partial \log P}{\partial \log \rho}\right)_s$	Specific heat at constant pressure, c_p, cal/(g)(°K)	Coefficient of viscosity, μ, micropoise	Coefficient of thermal conductivity, k, microcal/(sec)(cm)(°K)	Mean molecular weight, M	Equilibrium composition, mole fraction					
							HF	H_2	N_2	F	H	N
r = 1.2 (20.56 percent fuel by weight)												
4301	20.41	1.1626	1.5364	1822	3028	19.789	0.63642	0.00545	0.11587	0.19096	0.04219	0.00910
4000	10.58	1.1660	1.2776	1726	2417	20.188	.67021	.00307	.11990	.17387	.02705	.00589
2900	1.421	1.3056	.4141	1326	707	20.870	.72681	.00001	.12687	.14575	.00031	.00025
2200	.4614	1.3385	.3765	1046	518	20.879	.72747	.00000	.12705	.14547	.00000	.00000
r = 1.0 (23.70 percent fuel by weight)												
4306	20.41	1.1543	1.8535	1792	3555	19.110	0.65623	0.01750	0.12917	0.11118	0.07620	0.00972
4000	9.803	1.1510	1.6902	1698	3086	19.561	.69753	.01401	.13396	.08803	.06000	.00647
3000	.7276	1.1782	.8384	1353	1295	20.864	.81845	.00393	.14602	.01942	.01156	.00061
2800	.4504	1.2007	.6776	1276	1016	21.012	.83263	.00254	.14723	.01120	.00612	.00027
r = 0.8 (27.97 percent fuel by weight)												
4138	20.41	1.1654	1.5445	1674	2814	18.148	0.64692	0.05474	0.14680	0.04110	0.10365	0.00680
3900	12.14	1.1677	1.3803	1599	2423	18.420	.66971	.05639	.15015	.02866	.09048	.00463
2800	1.070	1.2195	.6863	1217	991	19.402	.73444	.08128	.16049	.00113	.02248	.00019
2400	.4602	1.2605	.5277	1067	698	19.565	.74165	.08929	.16192	.00013	.00699	.00002
r = 0.6 (34.11 percent fuel by weight)												
3735	20.41	1.1901	1.1739	1439	1900	16.916	0.57964	0.15665	0.16962	0.00701	0.08480	0.00229
3500	12.73	1.1944	1.0642	1365	1651	17.107	.58926	.16617	.17203	.00402	.06720	.00131
2400	1.308	1.2650	.5710	1002	713	17.695	.61363	.20147	.17862	.00004	.00623	.00001
1900	.4579	1.3138	.4721	826	505	17.746	.61544	.20488	.17914	.00000	.00053	.00000
r = 0.4 (43.71 percent fuel by weight)												
3049	20.41	1.2298	.8285	1104	1095	15.254	0.45165	0.32752	0.19723	0.00028	0.02314	0.00017
2800	12.74	1.2457	.7342	1033	926	15.333	.45417	.33415	.19831	.00010	.01321	.00006
1700	1.346	1.3280	.5218	697	476	15.435	.45731	.34295	.19967	.00000	.00007	.00000
1300	.4675	1.3516	.4950	562	368	15.436	.45733	.34300	.19968	.00000	.00000	.00000

1062

TABLE V. - COMPARISON OF CALCULATED PERFORMANCES OF MIXTURES OF LIQUID AMMONIA AND HYDRAZINE WITH LIQUID FLUORINE WITH EQUILIBRIUM AND FROZEN COMPOSITION ASSUMED DURING EXPANSION

[Combustion-chamber pressure, 300 lb/sq in. abs; stoichiometric equivalence ratio]

Parameters	Altitude			
	Sea level		30,000 ft	
	Equilibrium	Frozen	Equilibrium	Frozen
36.3 percent NH_3, 63.7 percent N_2H_4 by weight				
Specific impulse, I, lb-sec/lb	312.9	289.2	356.8	320.6
Characteristic velocity, c*, ft/sec	7057	6722	7057	6722
Coefficient of thrust, C_F	1.427	1.384	1.627	1.534
Nozzle-exit area to throat area, S_e/S_t	3.930	3.118	9.632	6.835
Nozzle-exit temperature, T_e, ^{o}K	3188	2044	2697	1475
Nozzle-exit molecular weight, M_e	20.86	19.15	21.27	19.15
87 percent NH_3, 13 percent N_2H_4 by weight				
Specific impulse, I, lb-sec/lb	311.3	288.2	354.7	319.5
Characteristic velocity, c*, ft/sec	7026	6697	7026	6697
Coefficient of thrust, C_F	1.426	1.384	1.624	1.535
Nozzle-exit area to throat area, S_e/S_t	3.912	3.125	9.505	6.855
Nozzle-exit temperature, T_e, ^{o}K	3127	2029	2613	1465
Nozzle-exit molecular weight, M_e	20.74	19.11	21.10	19.11

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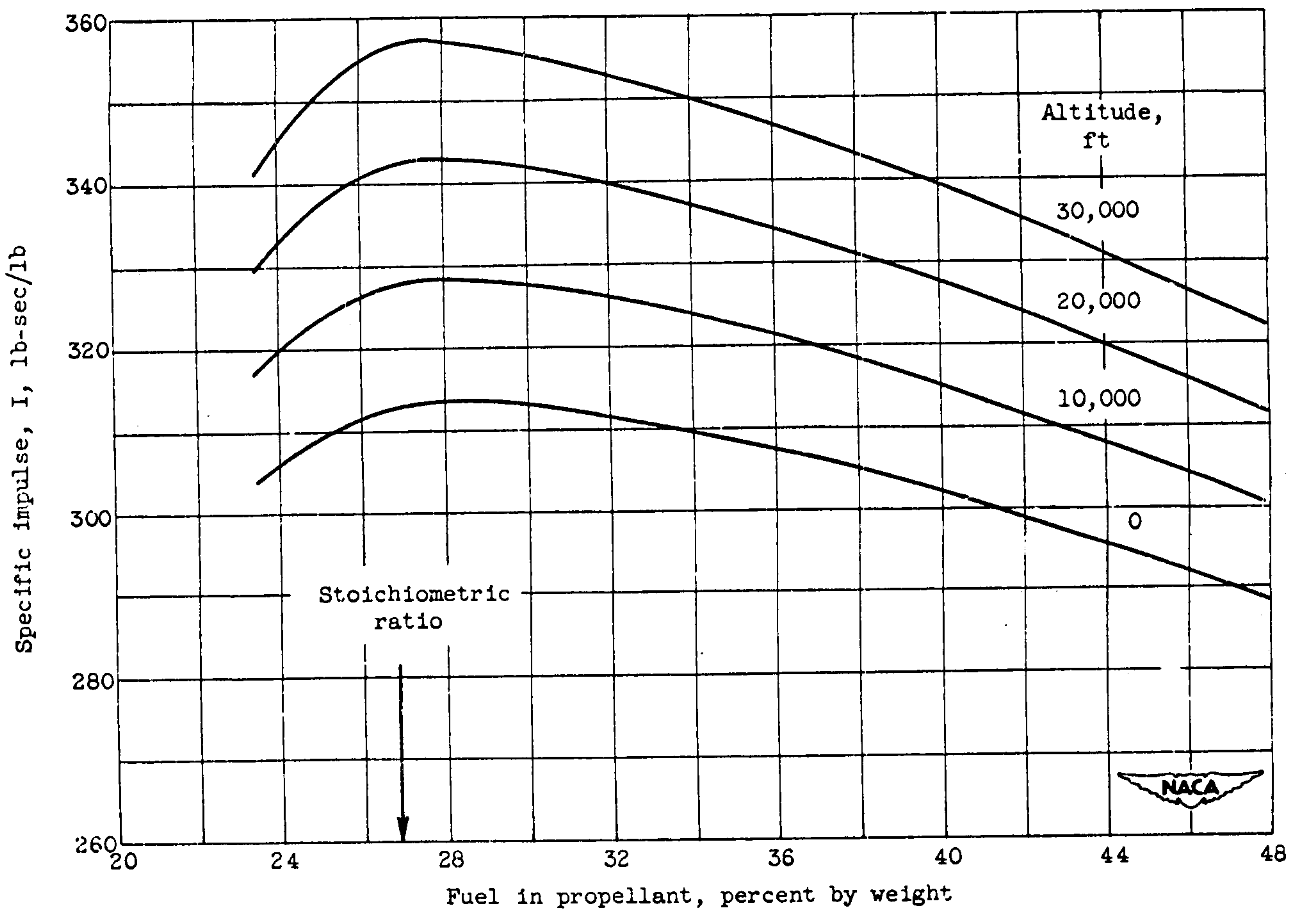

(a) Fuel, 36.3 percent ammonia and 63.7 percent hydrazine by weight.

Figure 1. - Theoretical specific impulse of mixture of liquid ammonia and hydrazine as fuel with liquid fluorine as oxidant. Isentropic expansion assuming equilibrium composition; combustion-chamber pressure, 300 pounds per square inch absolute; exit pressure corresponding to altitude indicated.

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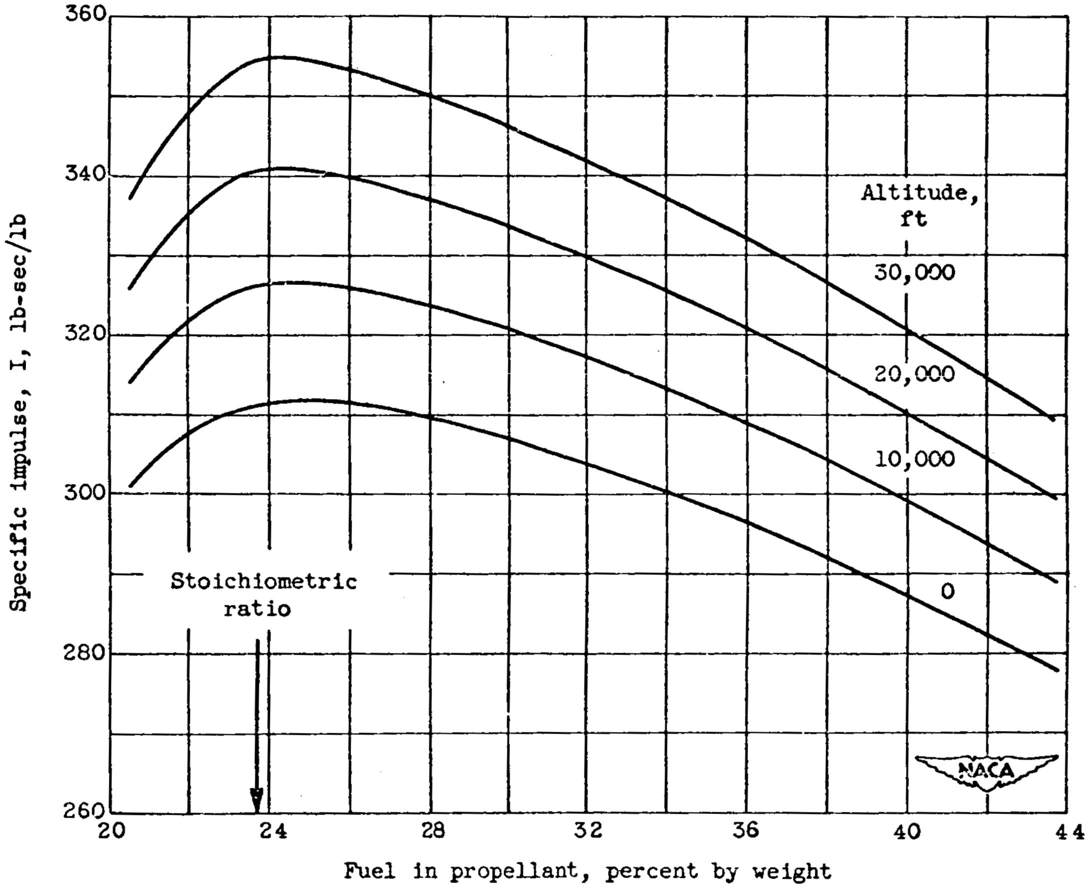

(b) Fuel, 87 percent ammonia and 13 percent hydrazine by weight.

Figure 1. - Concluded. Theoretical specific impulse of mixture of liquid ammonia and hydrazine as fuel with liquid fluorine as oxidant. Isentropic expansion assuming equilibrium composition; combustion-chamber pressure, 300 pounds per square inch absolute; exit pressure corresponding to altitude indicated.

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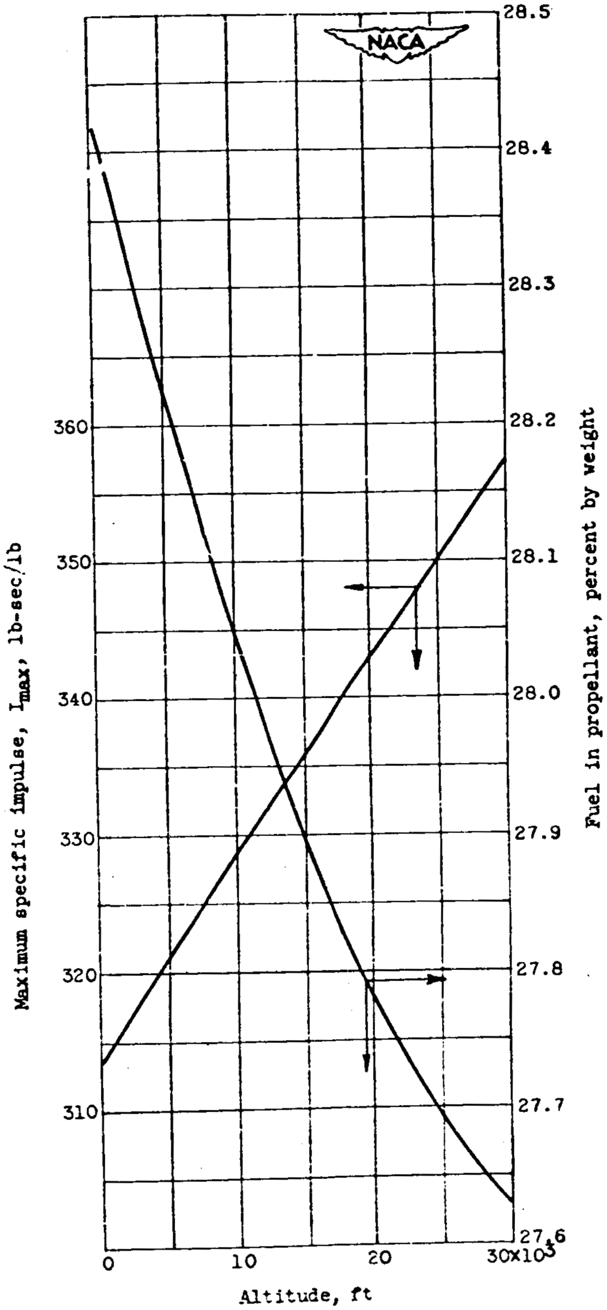

(a) Fuel, 36.3 percent ammonia and 63.7 percent hydrazine by weight.

Figure 2. - Maximum theoretical specific impulse and corresponding weight percent fuel in propellant of mixture of liquid ammonia and hydrazine as fuel with liquid fluorine as oxidant. Isentropic expansion assuming equilibrium composition; combustion-chamber pressure, 300 pounds per square inch absolute; exit pressure corresponding to altitude indicated.

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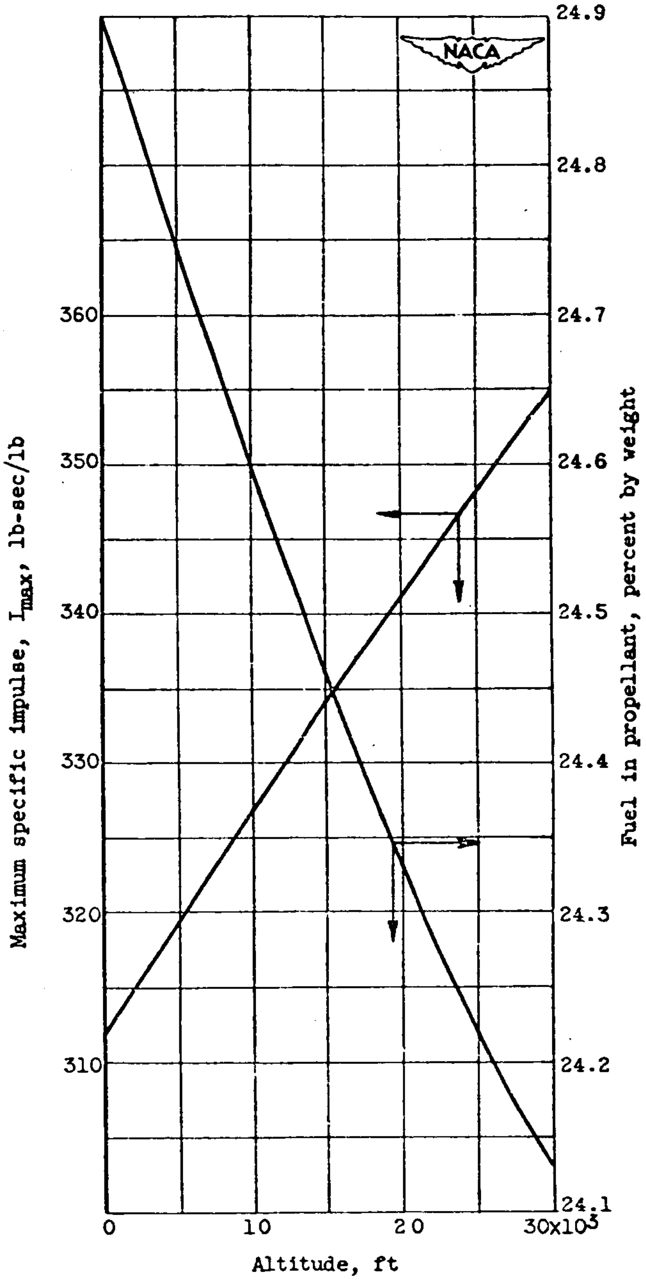

(b) Fuel, 87 percent ammonia and 13 percent hydrazine by weight.

Figure 2. - Concluded. Maximum theoretical specific impulse and corresponding weight percent fuel in propellant of mixture of liquid ammonia and hydrazine as fuel with liquid fluorine as oxidant. Isentropic expansion assuming equilibrium composition; combustion-chamber pressure, 300 pounds per square inch absolute; exit pressure corresponding to altitude indicated.

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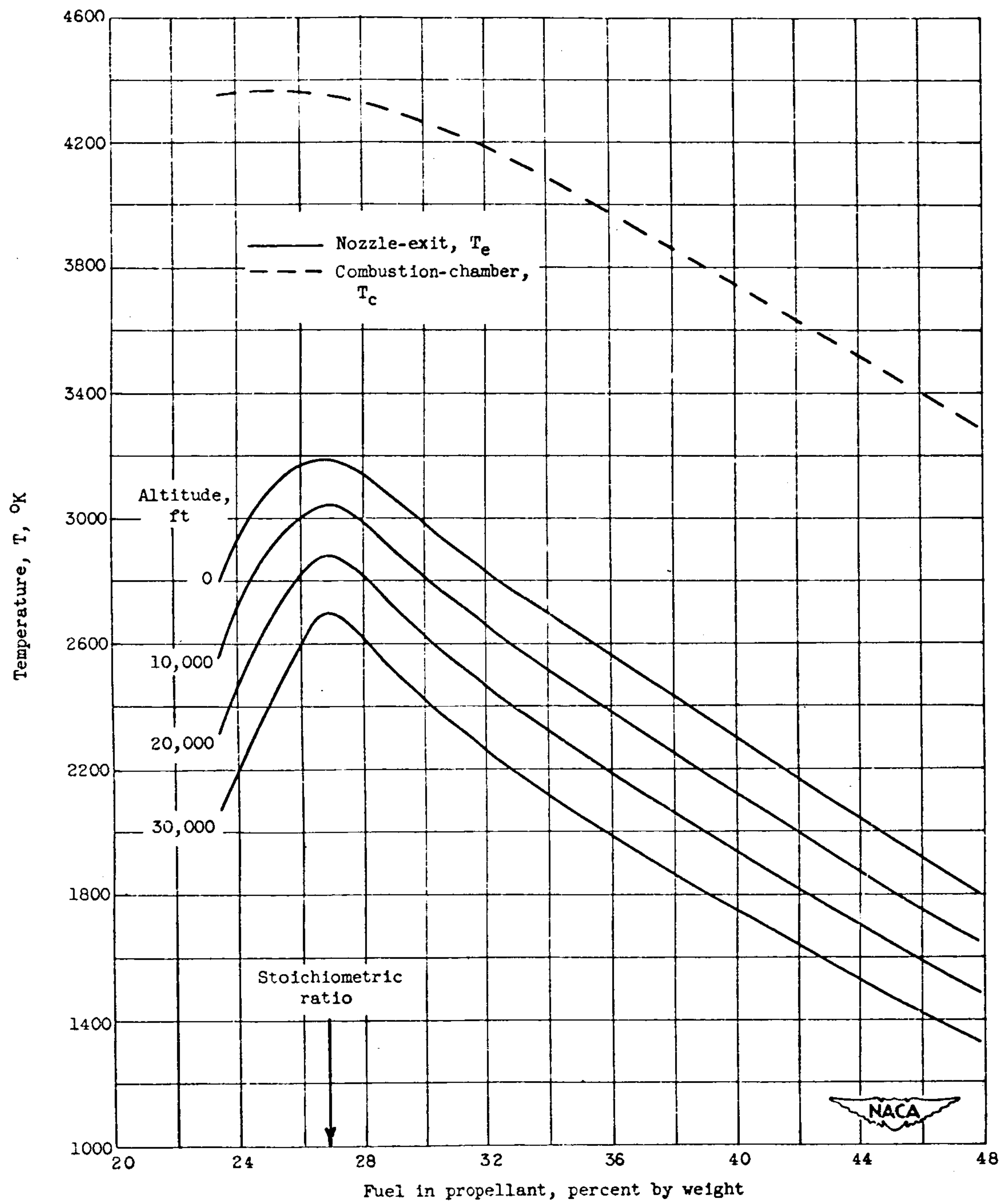

(a) Fuel, 36.3 percent ammonia and 63.7 percent hydrazine by weight.

Figure 3. - Theoretical combustion-chamber temperature and nozzle-exit temperature of mixture of liquid ammonia and hydrazine as fuel with liquid fluorine as oxidant. Isentropic expansion assuming equilibrium composition; combustion-chamber pressure, 300 pounds per square inch absolute; exit pressure corresponding to altitude indicated.

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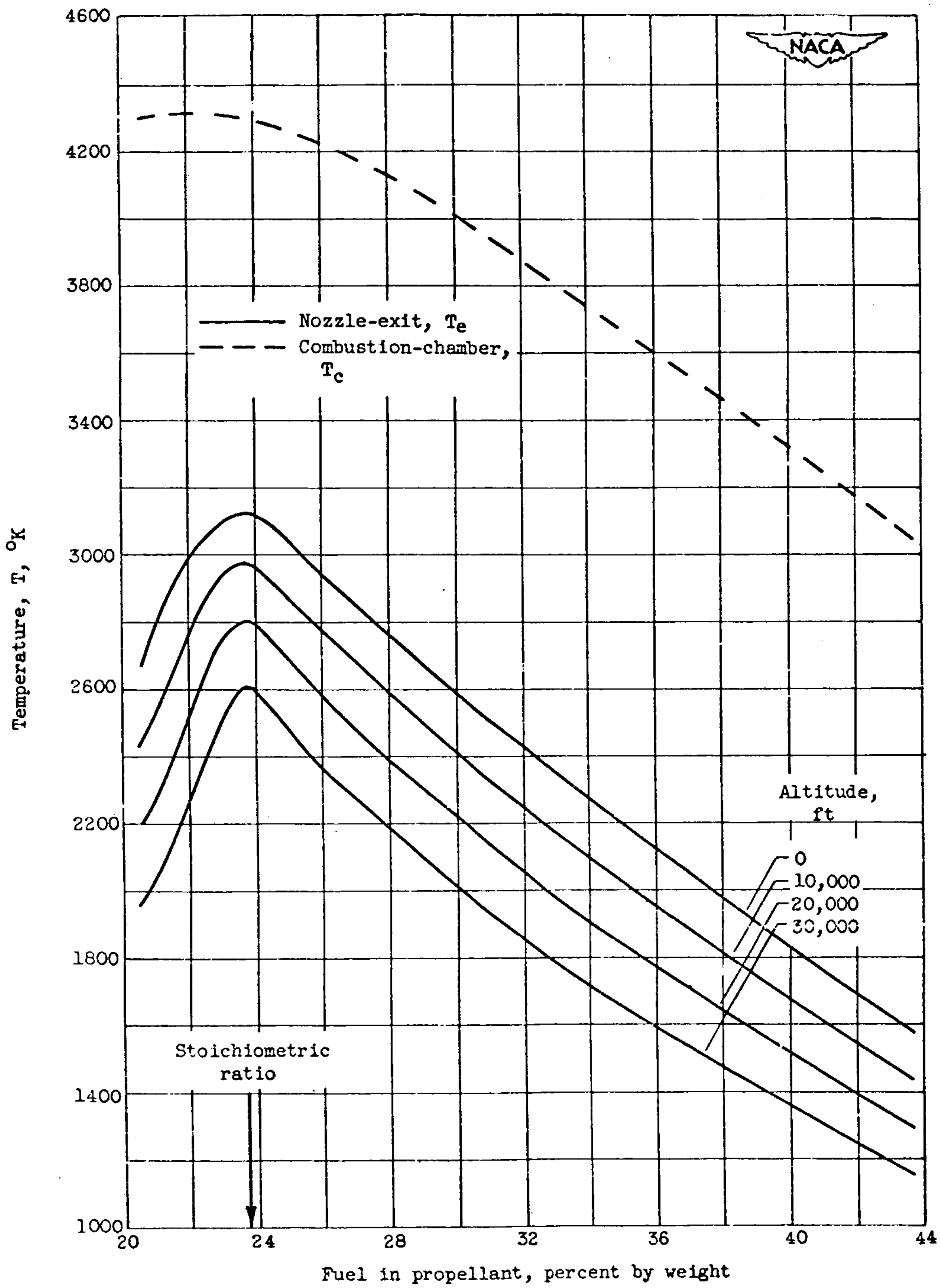

(b) Fuel, 87 percent ammonia and 13 percent hydrazine by weight.

Figure 3. - Concluded. Theoretical combustion-chamber temperature and nozzle-exit temperature of mixture of liquid ammonia and hydrazine as fuel with liquid fluorine as oxidant. Isentropic expansion assuming equilibrium composition; combustion-chamber pressure, 300 pounds per square inch absolute; exit pressure corresponding to altitude indicated.

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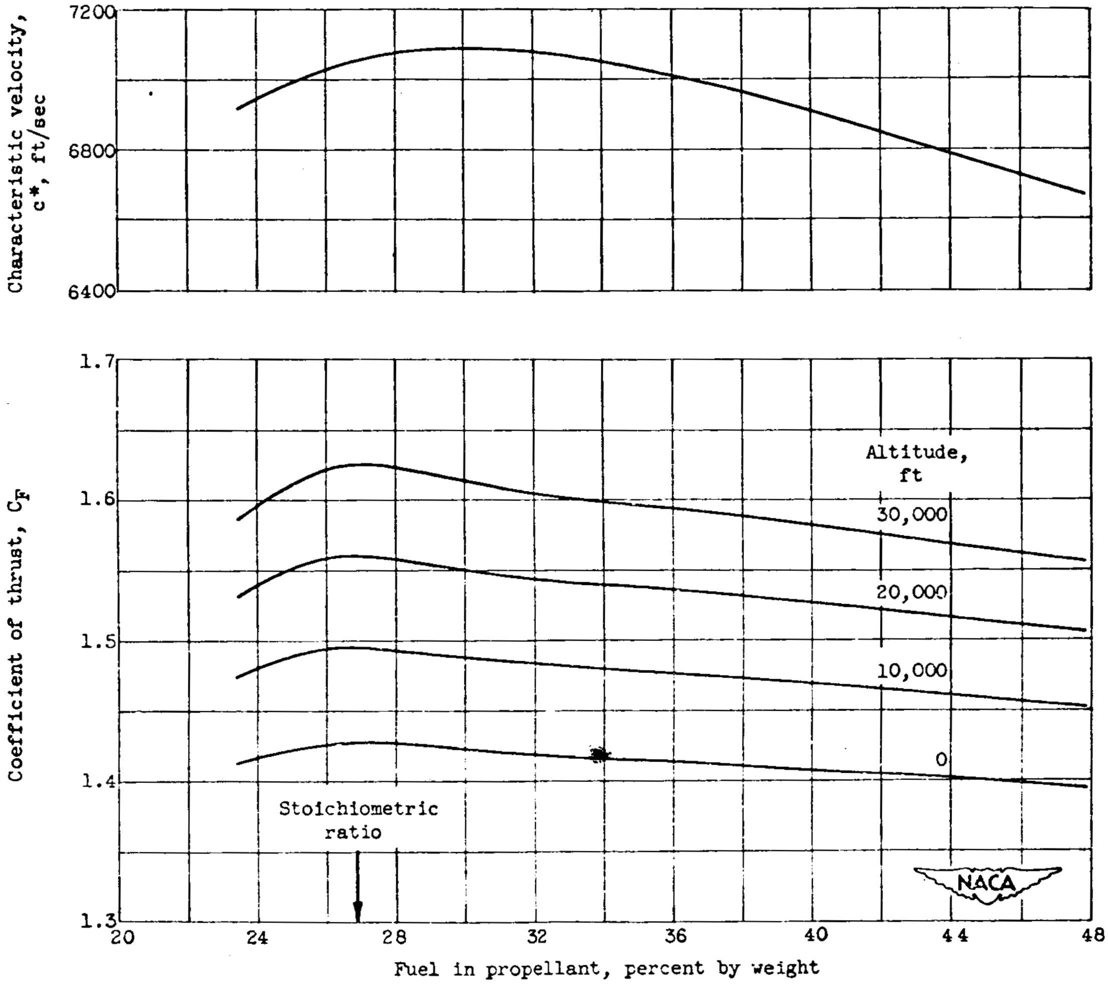

(a) Fuel, 36.3 percent ammonia and 63.7 percent hydrazine by weight.

Figure 4. - Theoretical characteristic velocity and coefficient of thrust of mixture of liquid ammonia and hydrazine as fuel with liquid fluorine as oxidant. Isentropic expansion assuming equilibrium composition; combustion-chamber pressure, 300 pounds per square inch absolute; exit pressure corresponding to altitude indicated.

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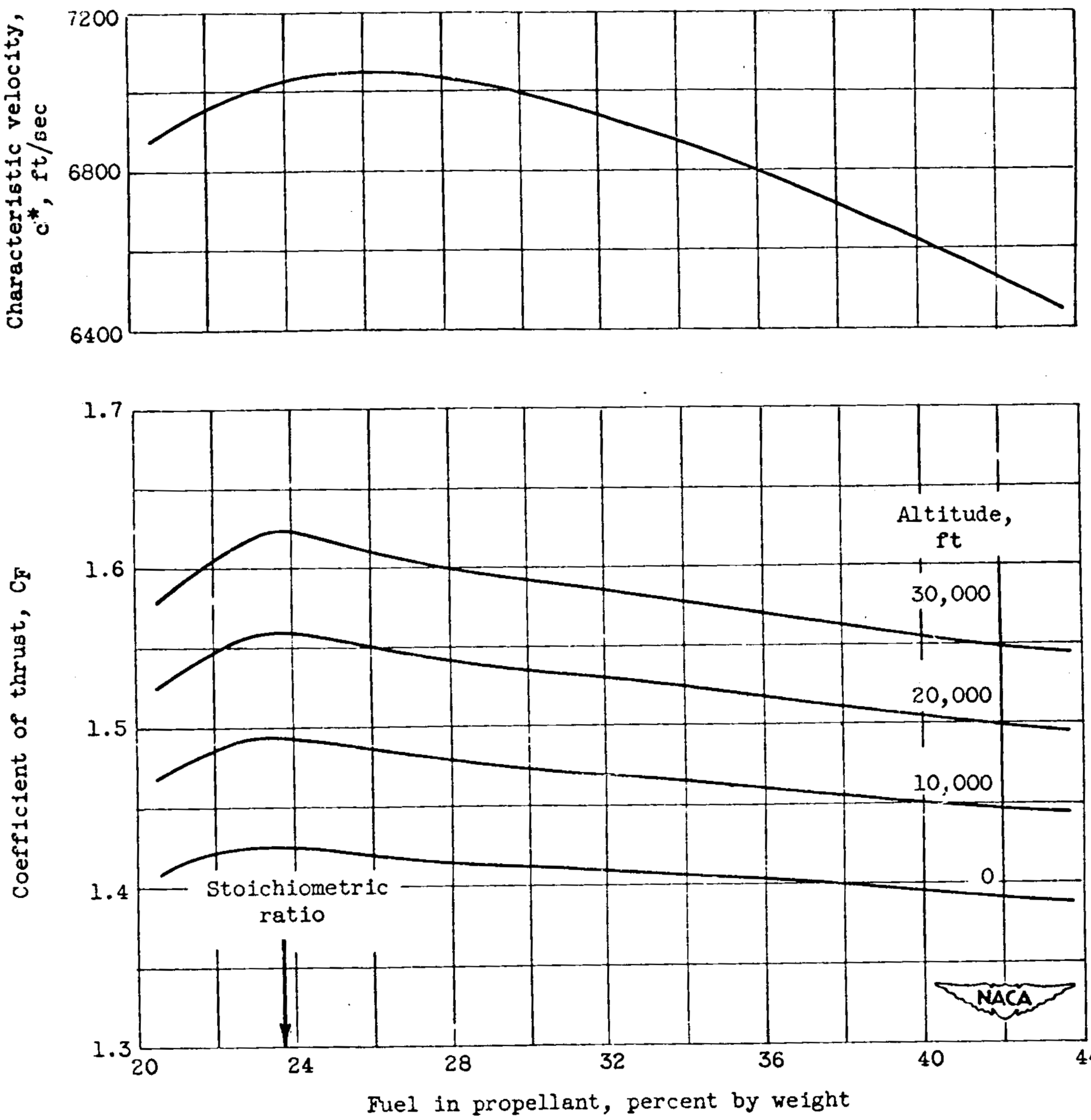

(b) Fuel, 87 percent ammonia and 13 percent hydrazine by weight.

Figure 4. - Concluded. Theoretical characteristic velocity and coefficient of thrust of mixture of liquid ammonia and hydrazine as fuel with liquid fluorine as oxidant. Isentropic expansion assuming equilibrium composition; combustion-chamber pressure, 300 pounds per square inch absolute; exit pressure corresponding to altitude indicated.

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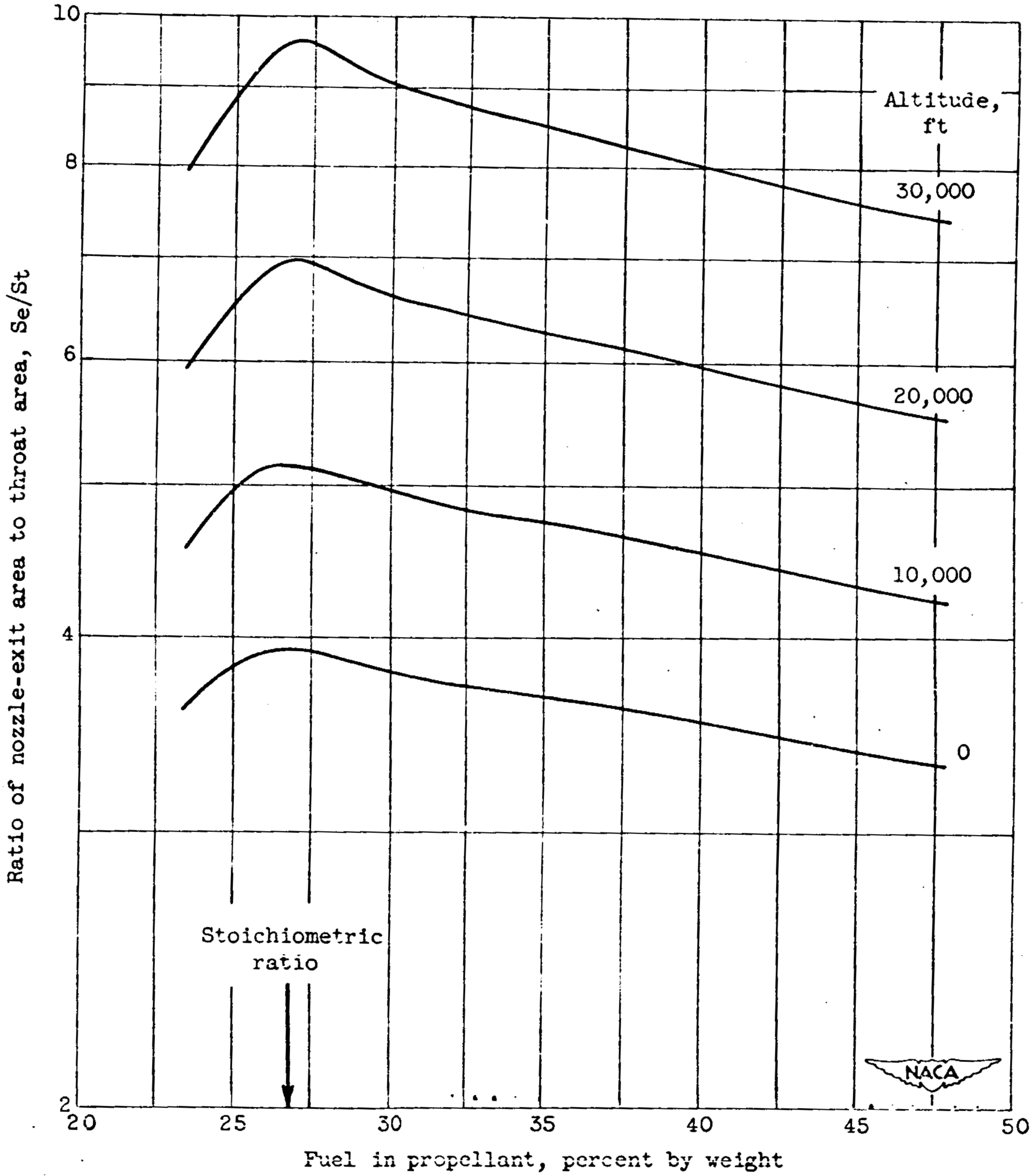

(a) Fuel, 36.3 percent ammonia and 63.7 percent hydrazine by weight.

Figure 5. - Theoretical ratio of nozzle-exit area to throat area for mixture of liquid ammonia and hydrazine as fuel with liquid fluorine as oxidant. Isentropic expansion assuming equilibrium composition; combustion-chamber pressure, 300 pounds per square inch absolute; exit pressure corresponding to altitude indicated.

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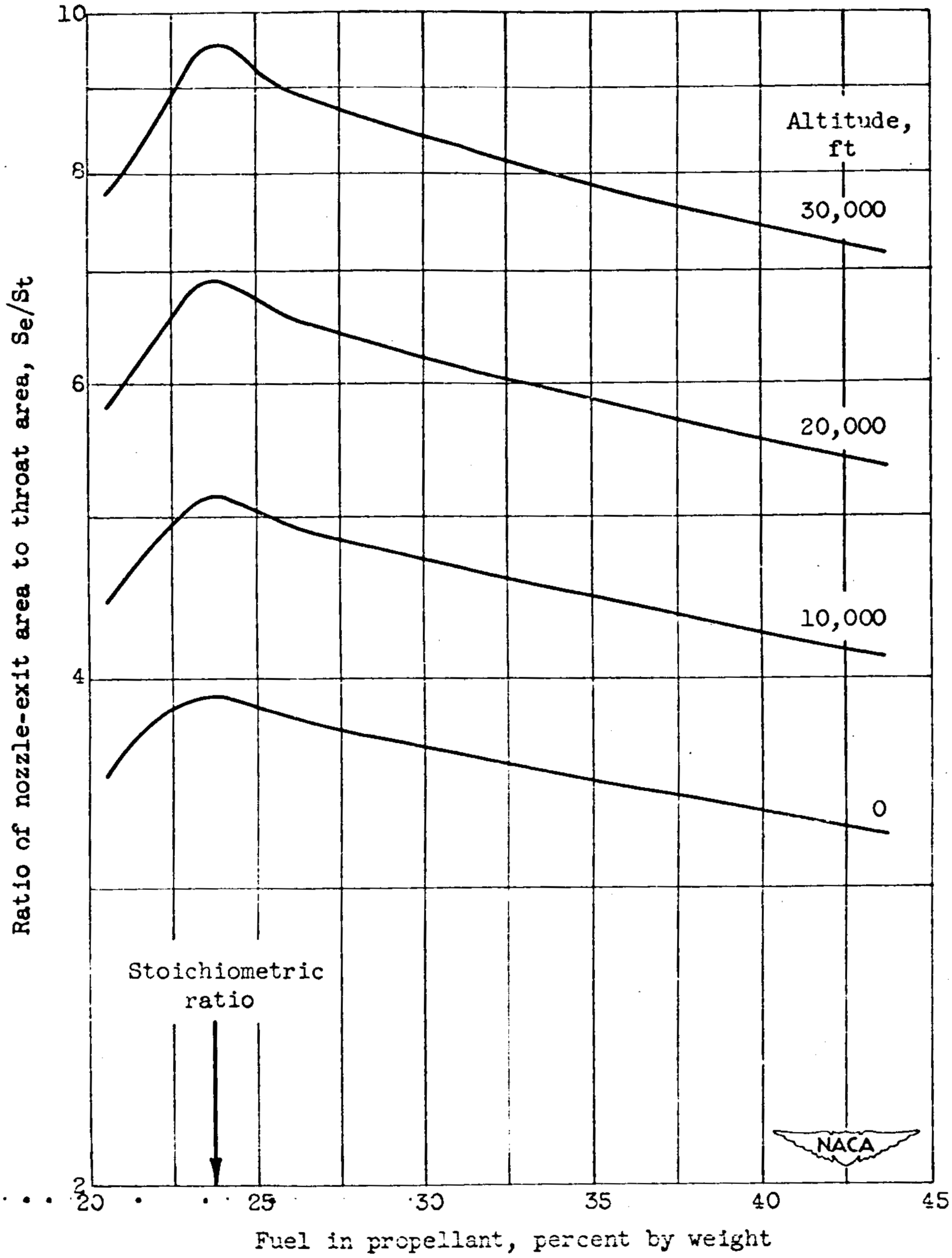

(b) Fuel, 87 percent ammonia and 13 percent hydrazine by weight.

Figure 5. - Concluded. Theoretical ratio of nozzle-exit area to throat area for mixture of liquid ammonia and hydrazine as fuel with liquid fluorine as oxidant. Isentropic expansion assuming equilibrium composition; combustion-chamber pressure, 300 pounds per square inch absolute; exit pressure corresponding to altitude indicated.

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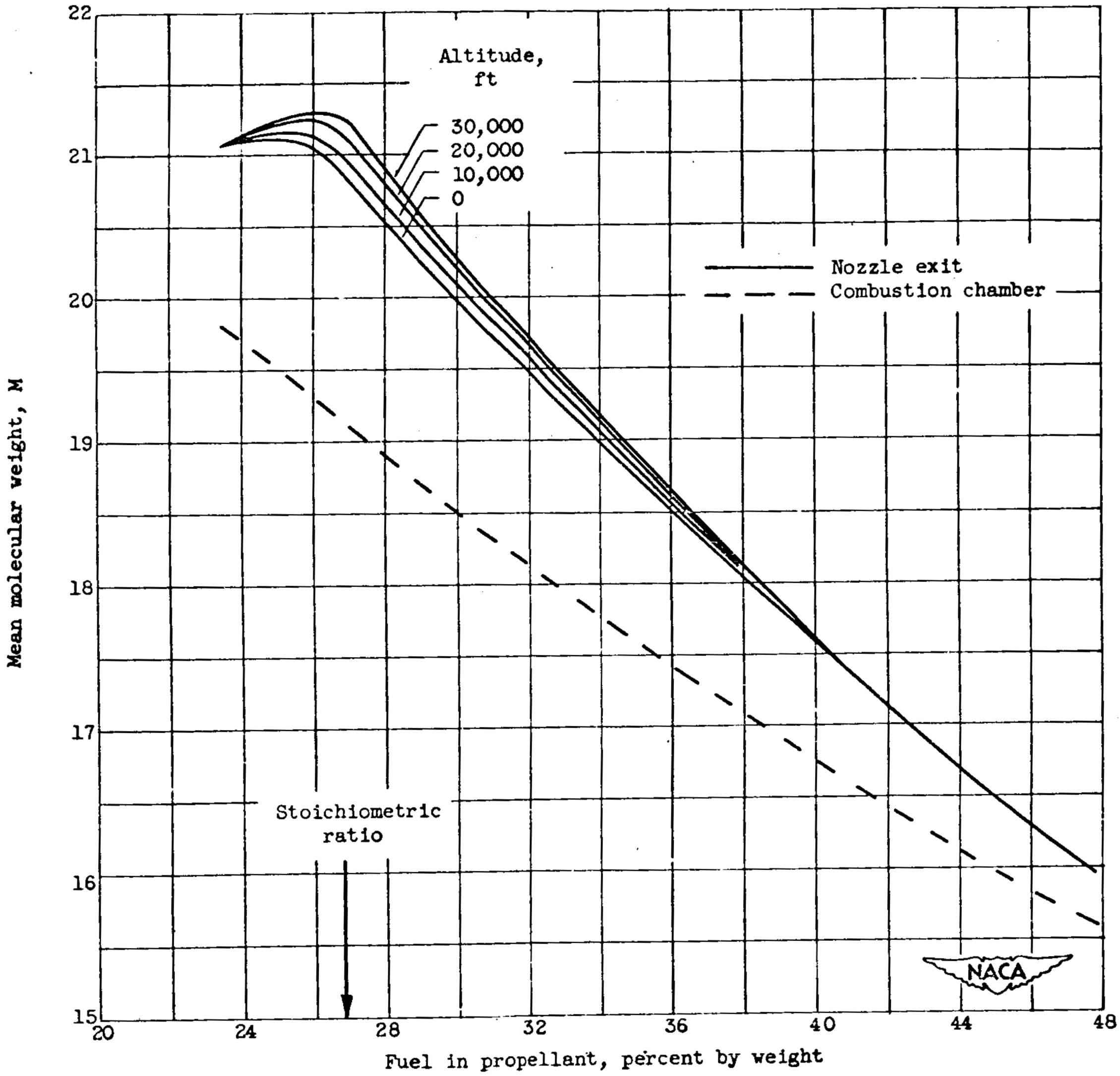

(a) Fuel, 36.3 percent ammonia and 63.7 percent hydrazine by weight.

Figure 6. - Theoretical mean molecular weight in combustion chamber and at nozzle exit for mixture of liquid ammonia and hydrazine as fuel with liquid fluorine as oxidant. Isentropic expansion assuming equilibrium composition; combustion-chamber pressure, 300 pounds per square inch absolute; exit pressure corresponding to altitude indicated.

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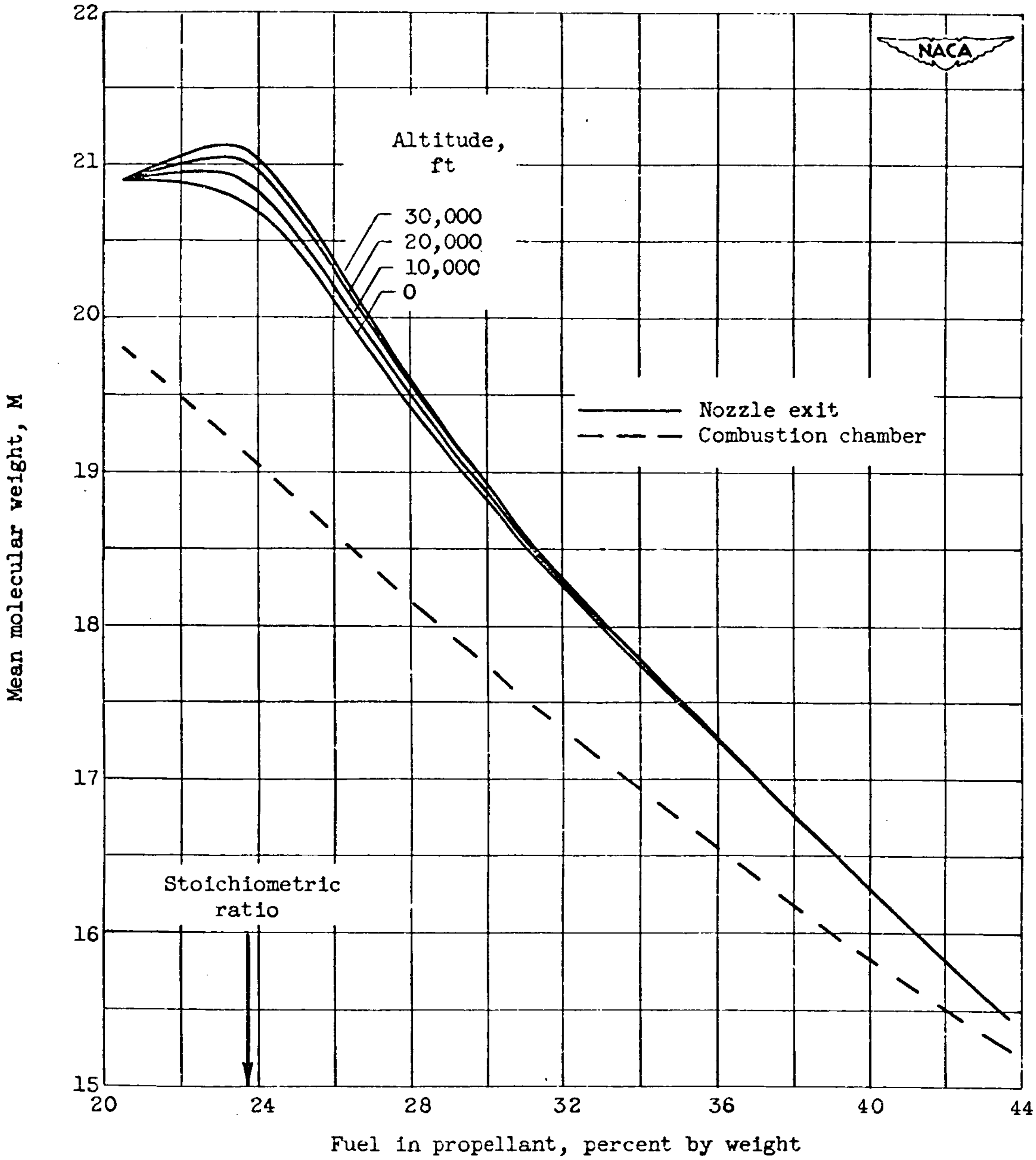

(b) Fuel, 87 percent ammonia and 13 percent hydrazine by weight.

Figure 6. - Concluded. Theoretical mean molecular weight in combustion chamber and at nozzle exit for mixture of liquid ammonia and hydrazine as fuel with liquid fluorine as oxidant. Isentropic expansion assuming equilibrium composition; combustion-chamber pressure, 300 pounds per square inch absolute; exit pressure corresponding to altitude indicated.

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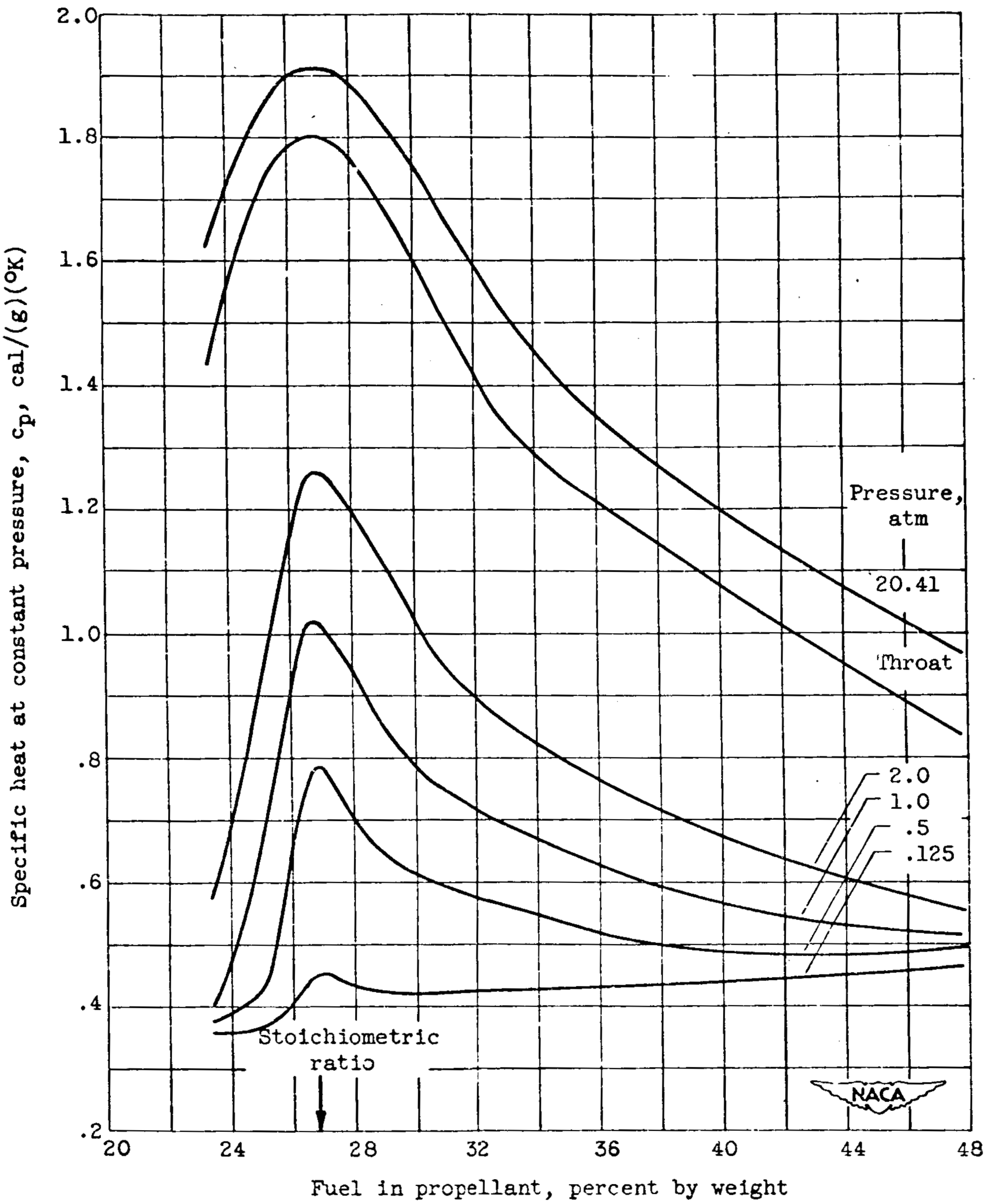

(a) Fuel, 36.3 percent ammonia and 63.7 percent hydrazine by weight.

Figure 7. - Theoretical specific heat at constant pressure of combustion products (including energy of dissociation) of mixture of liquid ammonia and hydrazine as fuel with liquid fluorine as oxidant. Isentropic expansion to pressures indicated assuming equilibrium composition; combustion-chamber pressure, 300 pounds per square inch absolute.

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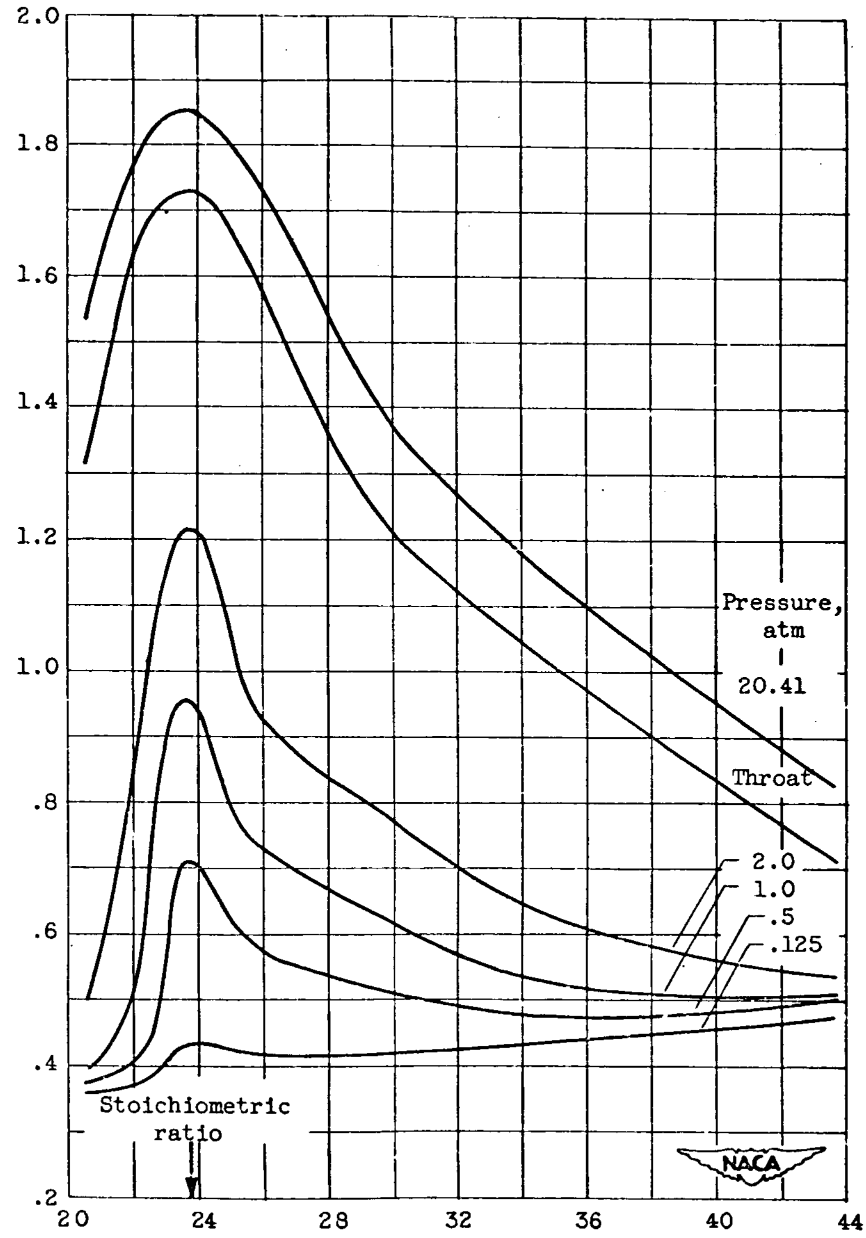

(b) Fuel, 87 percent ammonia and 13 percent hydrazine by weight.

Figure 7. - Concluded. Theoretical specific heat at constant pressure of combustion products (including energy of dissociation) of mixture of liquid ammonia and hydrazine as fuel with liquid fluorine as oxidant. Isentropic expansion to pressures indicated assuming equilibrium composition; combustion-chamber pressure, 300 pounds per square inch absolute.

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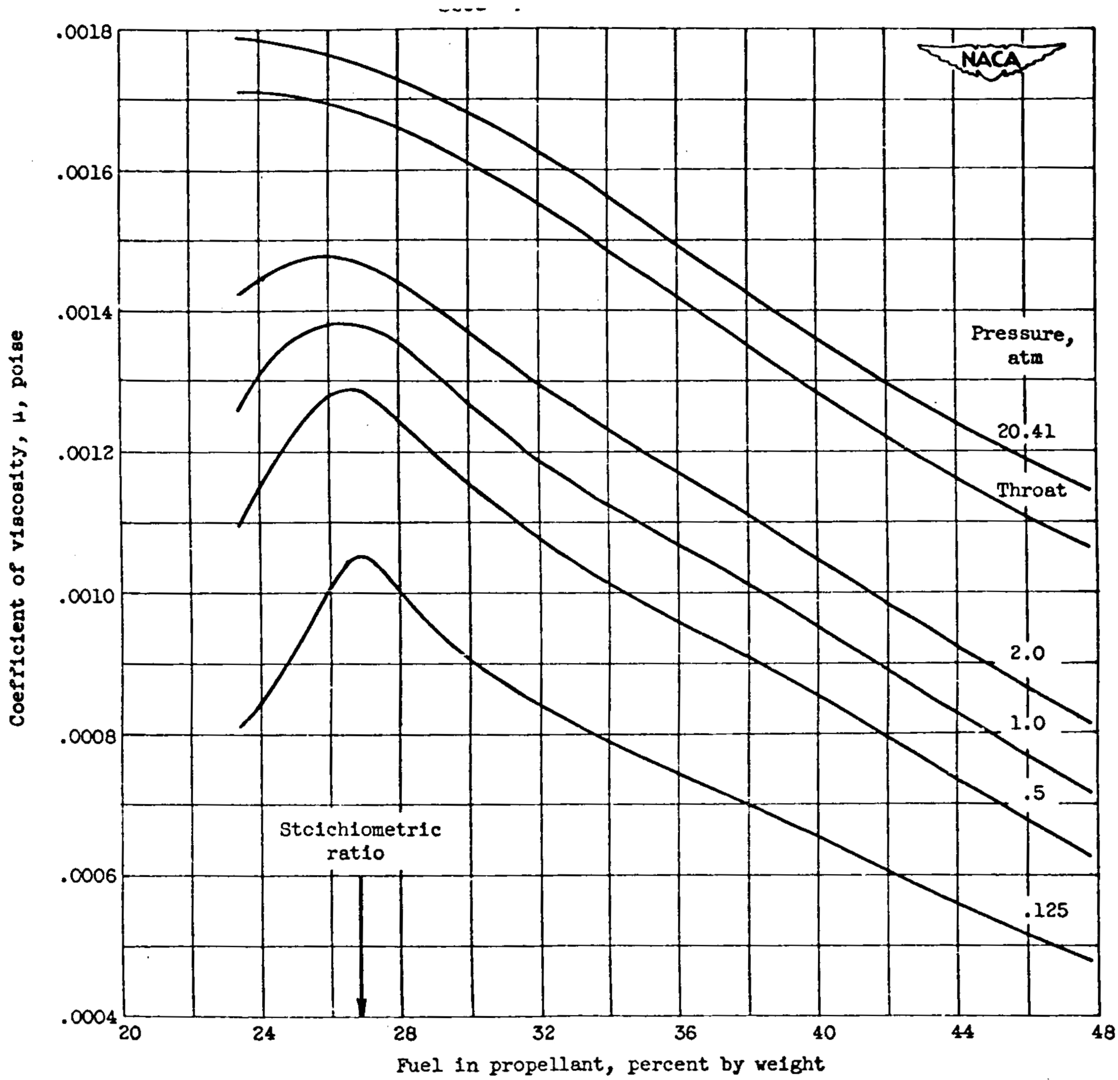

(a) Fuel, 36.3 percent ammonia and 63.7 percent hydrazine by weight.

Figure 8. - Theoretical coefficient of viscosity of combustion products of mixture of liquid ammonia and hydrazine as fuel with liquid fluorine as oxidant. Isentropic expansion to pressures indicated assuming equilibrium composition; combustion-chamber pressure, 300 pounds per square inch absolute.

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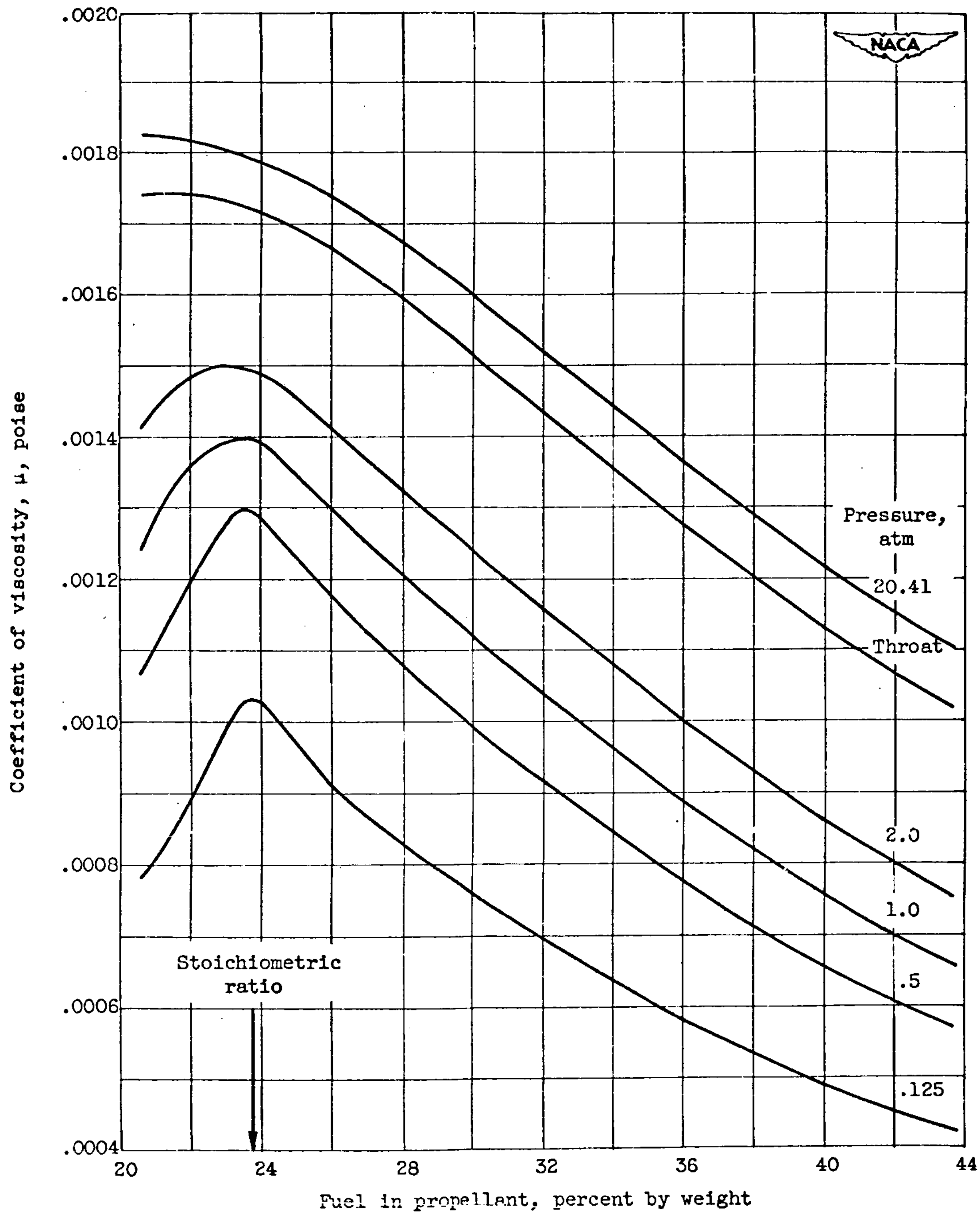

(b) Fuel, 87 percent ammonia and 13 percent hydrazine by weight.

Figure 8. - Concluded. Theoretical coefficient of viscosity of combustion products of mixture of liquid ammonia and hydrazine as fuel with liquid fluorine as oxidant. Isentropic expansion to pressures indicated assuming equilibrium composition; combustion-chamber pressure, 300 pounds per square inch absolute.

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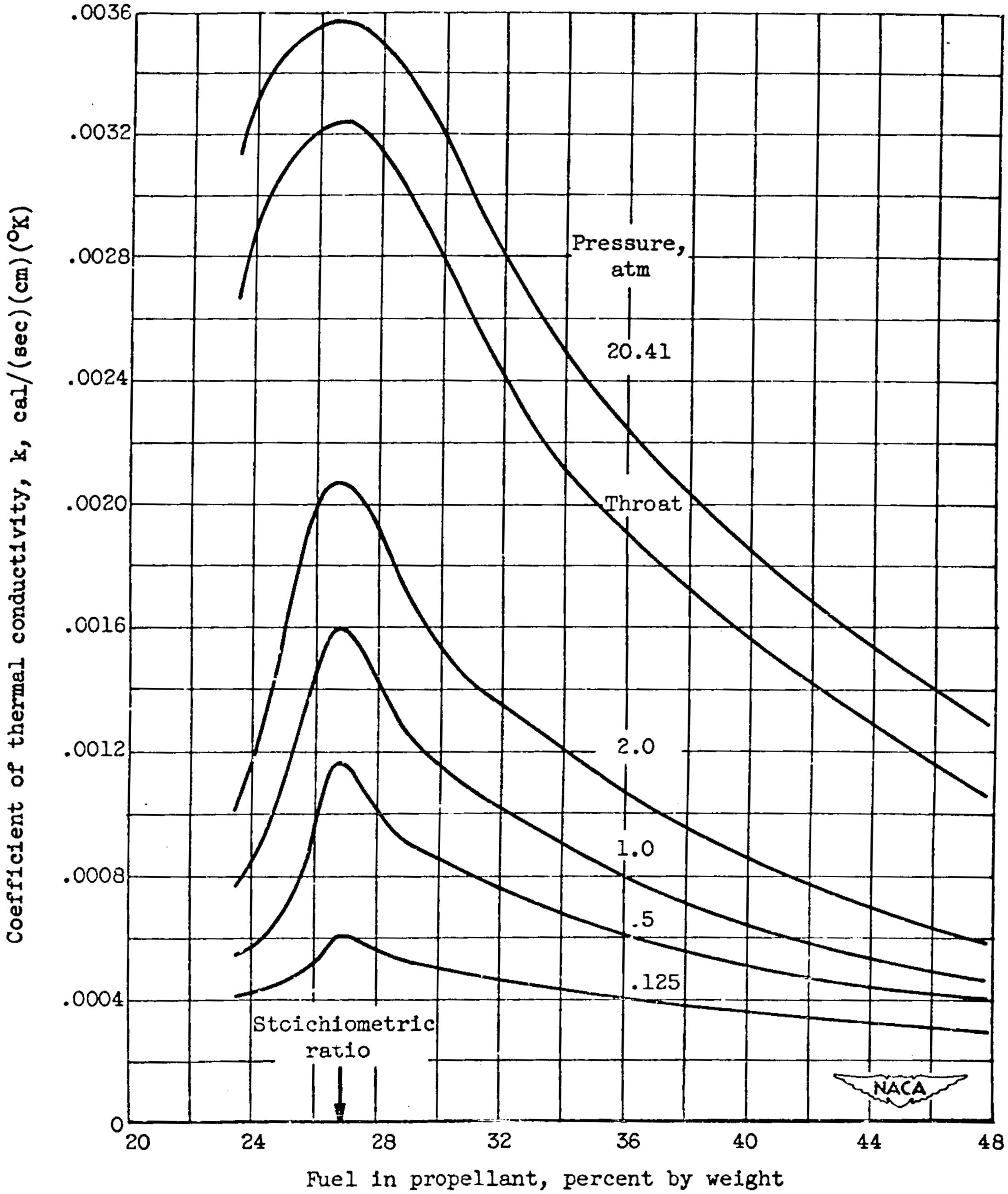

(a) Fuel, 36.3 percent ammonia and 63.7 percent hydrazine by weight.

Figure 9. - Theoretical coefficient of thermal conductivity of combustion products of mixture of liquid ammonia and hydrazine as fuel with liquid fluorine as oxidant. Isentropic expansion to pressures indicated assuming equilibrium composition; combustion-chamber pressure, 300 pounds per square inch absolute.

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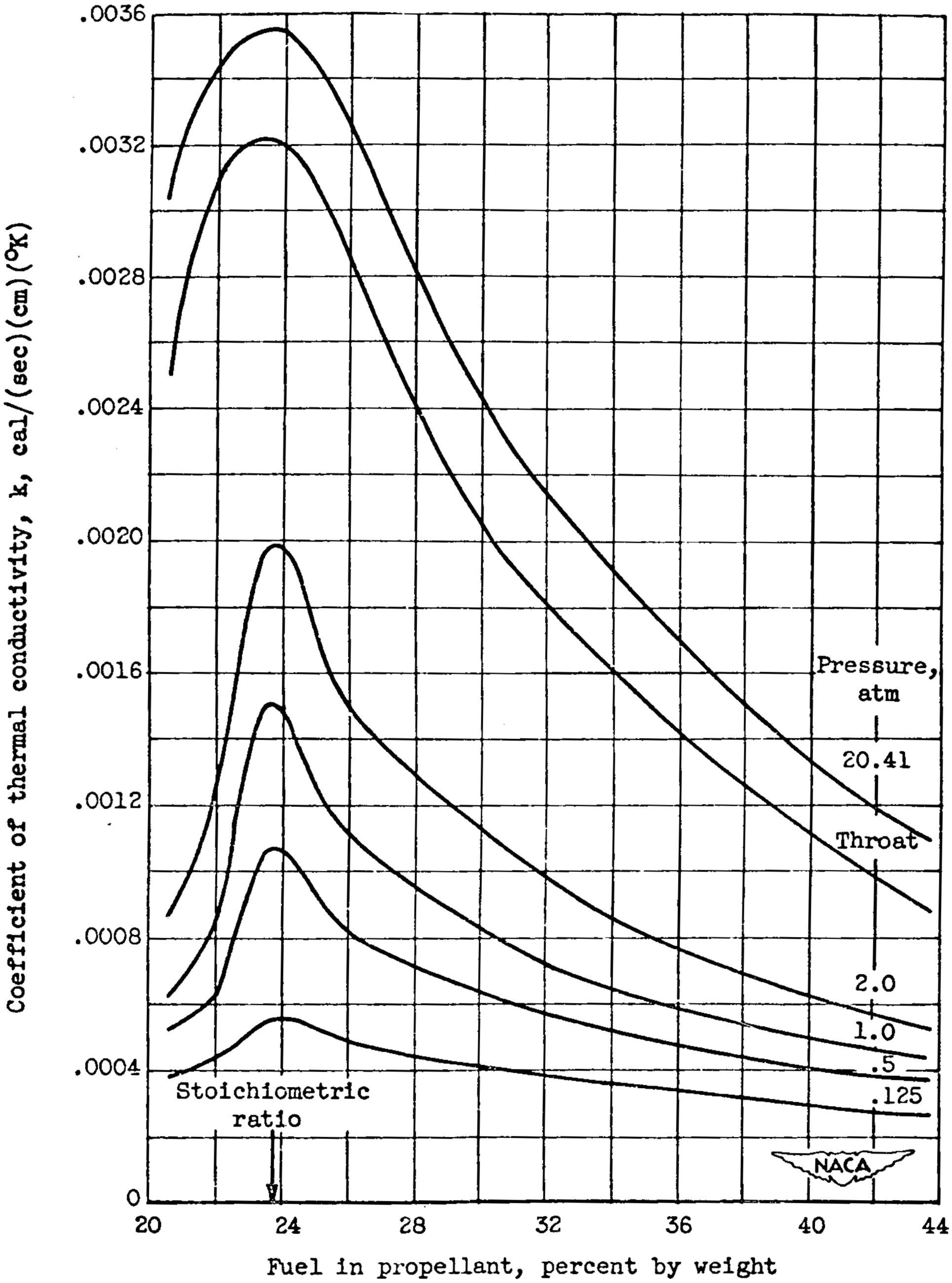

(b) Fuel, 87 percent ammonia and 13 percent hydrazine by weight.

Figure 9. - Concluded. Theoretical coefficient of thermal conductivity of combustion products of mixture of liquid ammonia and hydrazine as fuel with liquid fluorine as oxidant. Isentropic expansion to pressures indicated assuming equilibrium composition; combustion-chamber pressure, 300 pounds per square inch absolute.

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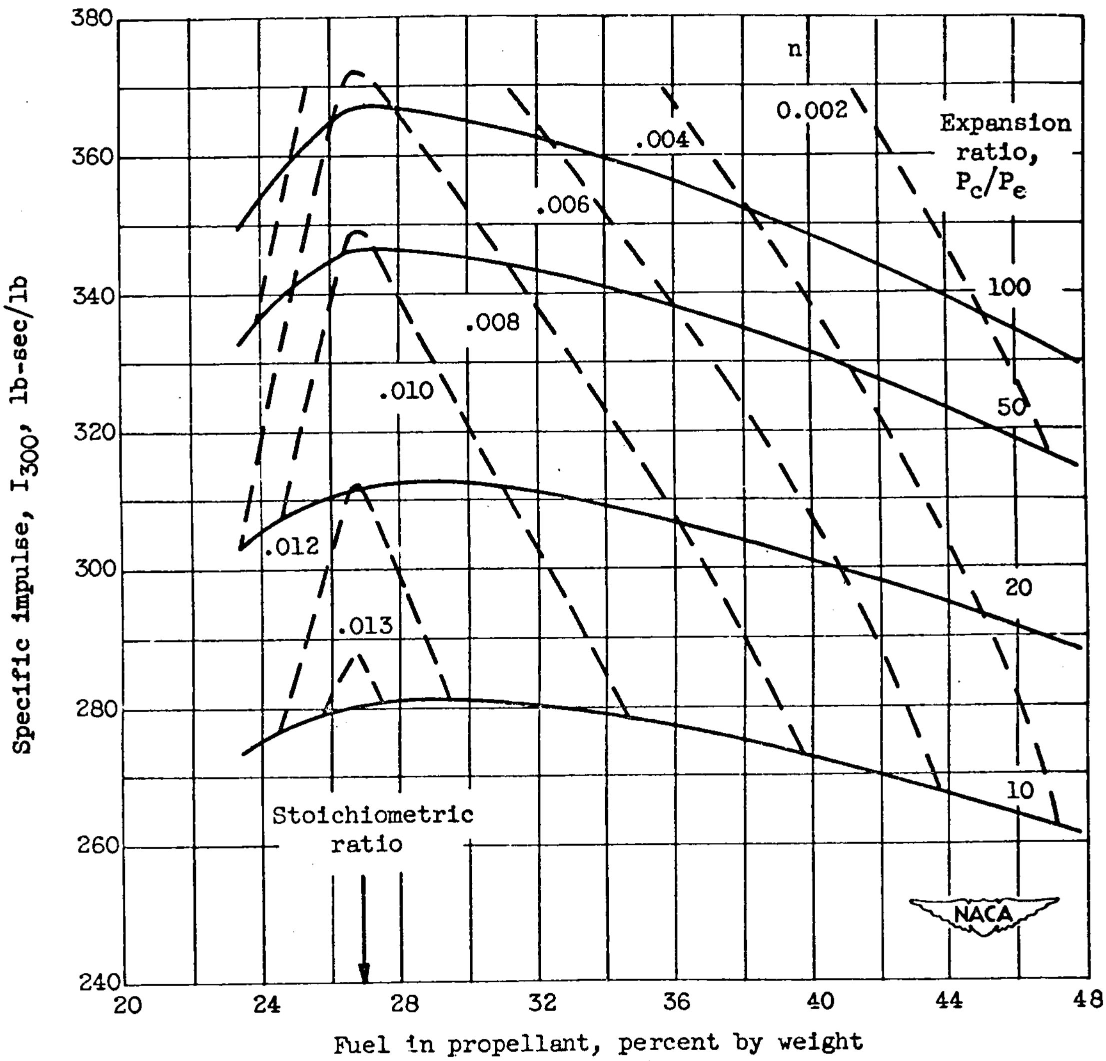

(a) Fuel, 36.3 percent ammonia and 63.7 percent hydrazine by weight; oxidant, liquid fluorine.

Figure 10. - Theoretical specific impulse for chamber pressure of 300 pounds per square inch absolute and exponent n for equation $I = I_{300} (P_c/300)^n$. Isentropic expansion to expansion ratio indicated assuming equilibrium composition.

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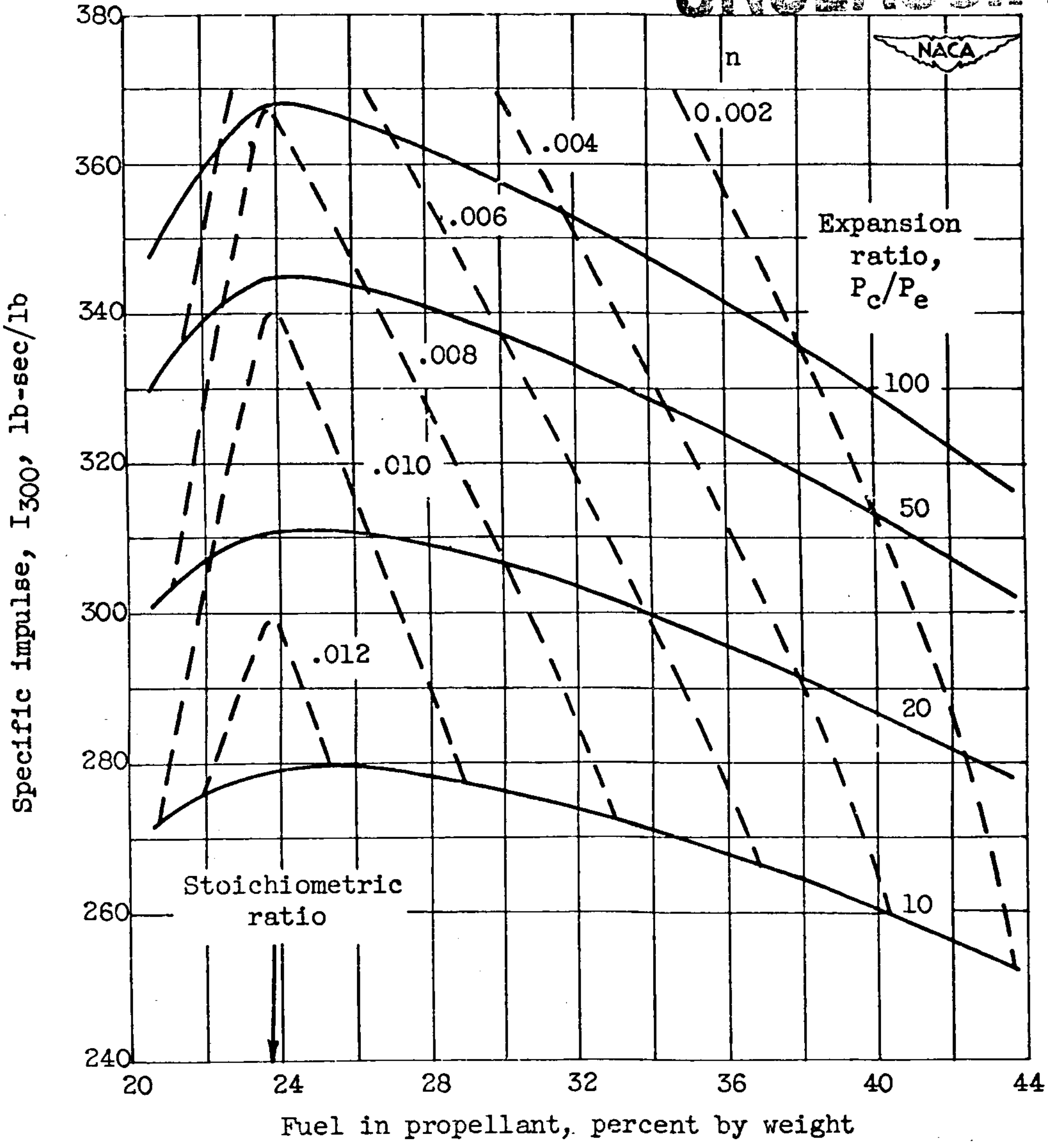

(b) Fuel, 87 percent ammonia and 13 percent hydrazine by weight; oxidant, liquid fluorine.

Figure 10. - Continued. Theoretical specific impulse for chamber pressure of 300 pounds per square inch absolute and exponent n for equation $I = I_{300} (P_c/300)^n$. Isentropic expansion to expansion ratio indicated assuming equilibrium composition.

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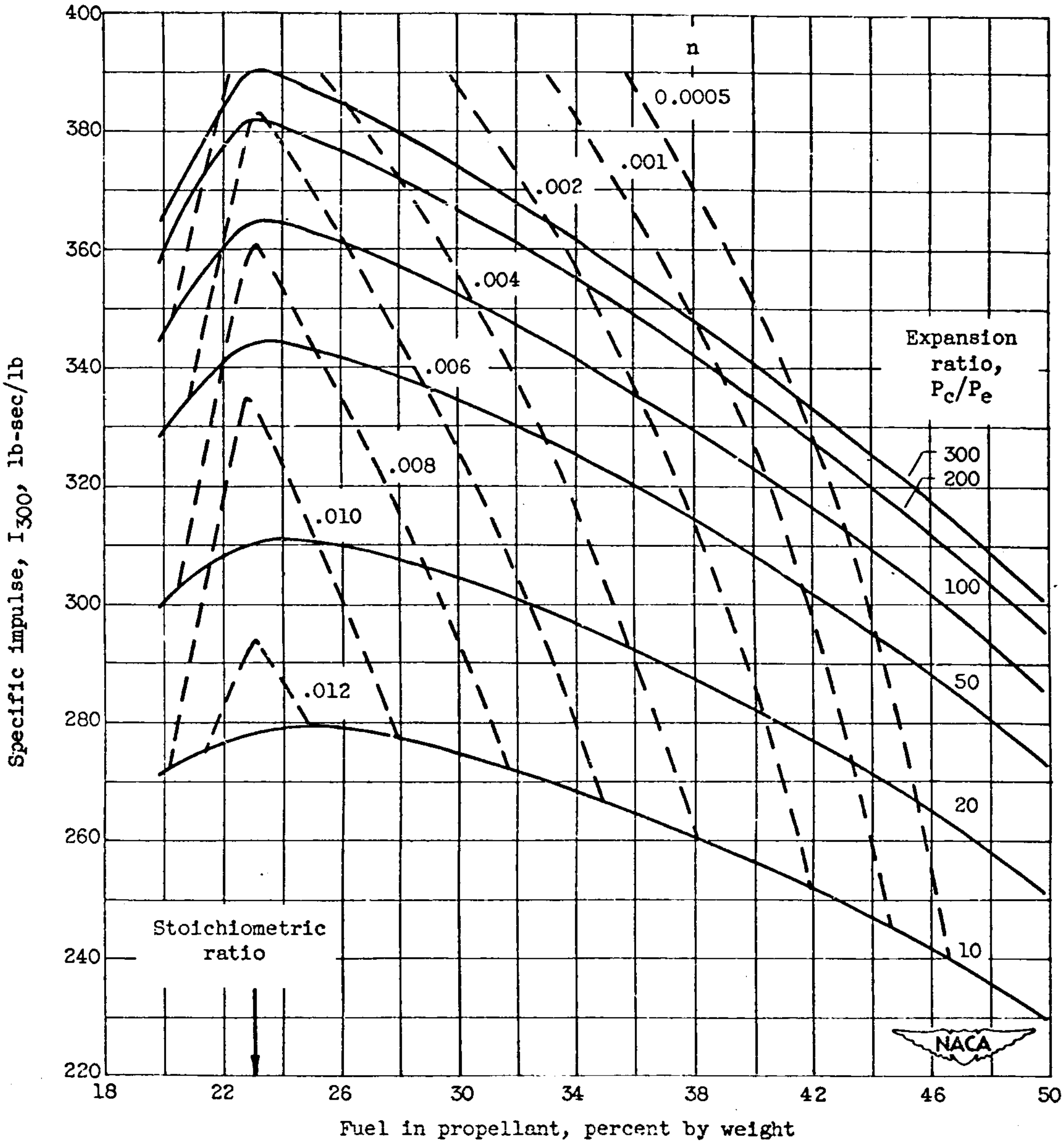

(c) Fuel, liquid ammonia; oxidant, liquid fluorine.

Figure 10. - Continued. Theoretical specific impulse for chamber pressure of 300 pounds per square inch absolute and exponent n for equation $I = I_{300} (P_c/300)^n$. Isentropic expansion to expansion ratio indicated assuming equilibrium composition.

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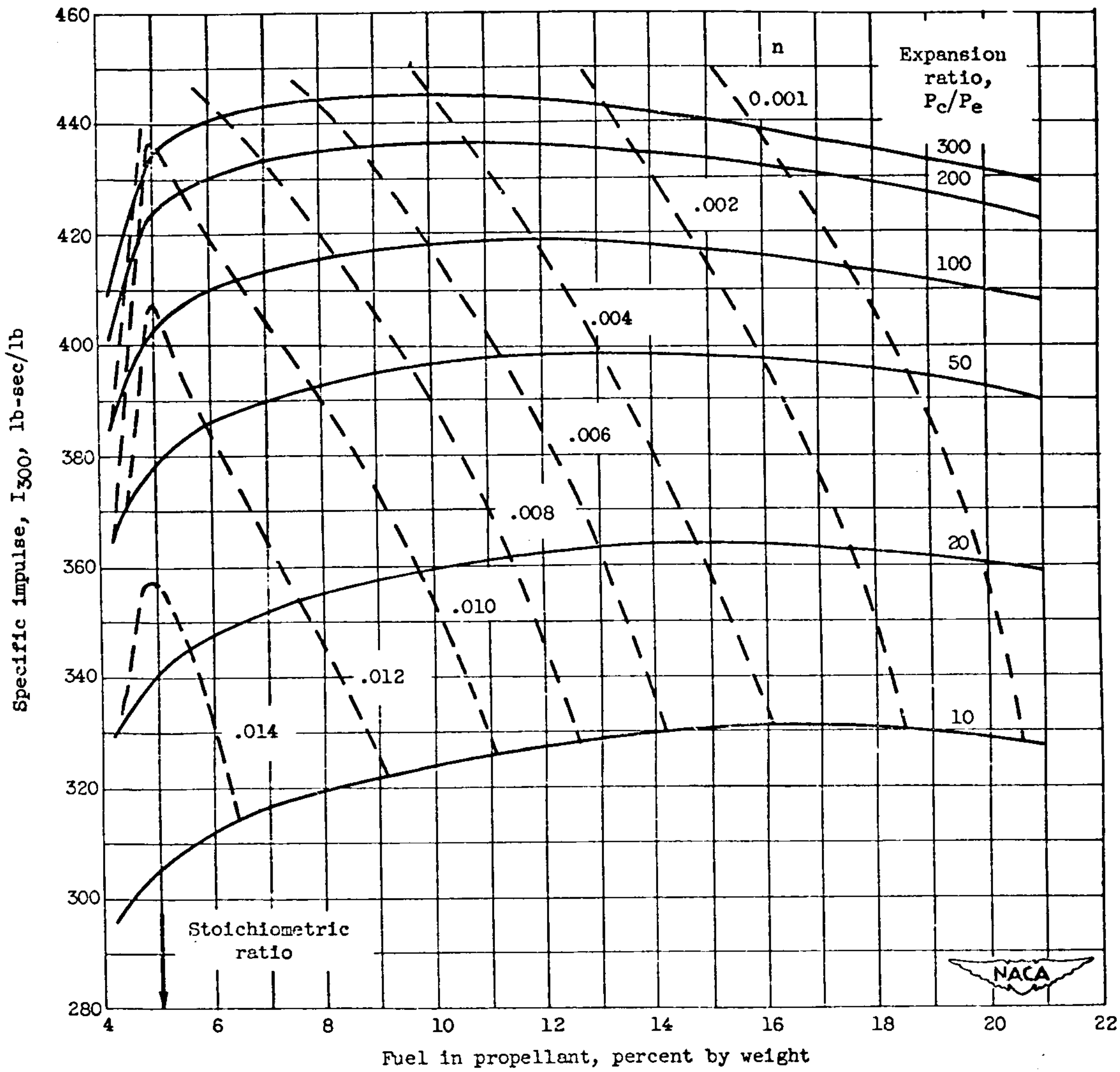

(d) Fuel, liquid hydrogen; oxidant, liquid fluorine.

Figure 10. - Concluded. Theoretical specific impulse for chamber pressure of 300 pounds per square inch absolute and exponent n for equation $I = I_{300}\,(P_c/300)^n$. Isentropic expansion to expansion ratio indicated assuming equilibrium composition.

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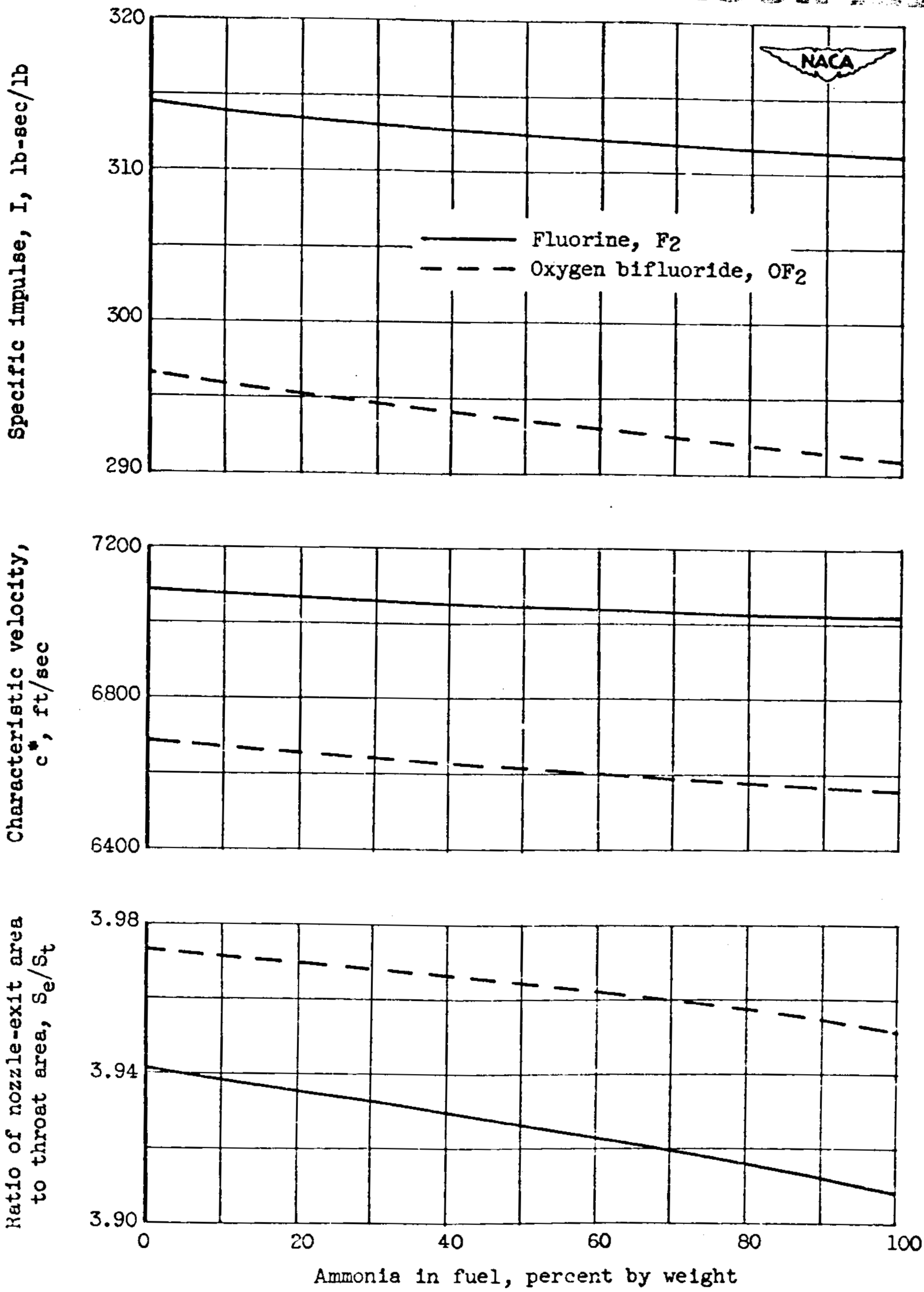

Figure 11. - Example of nearly linear variation of theoretical specific impulse, characteristic velocity, and ratio of nozzle-exit area to throat area for mixtures of liquid ammonia and hydrazine as fuel with liquid fluorine or liquid oxygen bifluoride as oxidant. Stoichiometric equivalence ratio; isentropic expansion assuming equilibrium composition; combustion-chamber pressure, 300 pounds per square inch absolute; exit pressure, 1 atmosphere. (OF_2 curves taken from fig. 7 of ref. 10.)